Comprehensive Assessment

On Streetcar Propulsion Technology

Prepared for
Council of the District of Columbia

Prepared by
District Department of Transportation

July 31, 2014

Executive Summary

This **Comprehensive Assessment on Streetcar Propulsion Technology** is a report prepared for the District Department of Transportation in order to assess the feasibility of various non-aerial motive power technologies for streetcar propulsion in the District of Columbia.

It is important to note that there is no system, national or international, which relies completely on non-aerial motive power technologies for streetcar propulsion. Used in combination with catenary powered systems the non-aerial motive power (off-wire) systems propel the streetcar for short distances up to one mile. These off-wire systems are fairly new, have limited applications, and the technologies continue to evolve. With limited applications there are concerns about safety and reliability of the system.

The available off-wire technologies fall into one of the two categories:

- On-Board Energy Storage Systems
- Ground Level Power Systems

Based on initial research completed in 2011 and additional research conducted in 2013-14, on behalf of DDOT, HDR has analyzed and consolidated the available off-wire technologies with pros and cons of each with emphasis on their applicability in the DC environment. The analysis addressed the rough-order-of-magnitude costs and feasibility of installing a new off-wire system as well as the rough-order-of-magnitude costs and feasibility of converting a catenary-based system to an off-wire system.

The *Summary Assessment on Streetcar Propulsion Technology,* attached as Section A, represents the core findings of this report and responds to the questions posed by the Transportation Infrastructure Amendment Act of 2010 (TIAA) regarding DC Streetcar:

1. Identify advances in propulsion technology and better understand the “state of the art”

2. Discuss the feasibility of converting to non-aerial motive power where overhead wires have been installed.

3. Discuss the feasibility of converting to non-aerial motive power for proposed (future planned) streetcar segments.

4. Recommended amendments to the TIAA, including a potential sunset date.

The state of off-wire (or wireless) motive power or propulsion systems technology for streetcars is evolving, but not yet mature. Two main categories of solutions exist. One of these categories, Ground Level Power Supply Systems (GLPSS), generally involves proprietary systems that have limited proven applications and that may have higher short and long term costs. The second category, On-Board Energy Storage Systems (OESS), generally focuses on battery and super capacitor technologies. These technologies are also limited in their proven applications, having only been implemented in dedicated rights-of-way, in relatively flat areas, over limited distances and in favorable climates. These technologies would face challenges operating in the District's more difficult environment (topography, weather, traffic conditions).

In general, the existing level of off-wire propulsion technology is not seen as mature enough to fully achieve the District's ultimate goal of a completely off-wire system in the near term. As these technologies continue to evolve, the District's goal would be achievable. Therefore, it is anticipated that the District will gradually implement an off-wire system. In the near term, proven overhead contact system (OCS)-based technologies will form the basis of the system, with limited application of off-wire technologies in the most sensitive areas to the extent possible. As technologies advance, the amount of off-wire operations will be gradually increased.

In addition to the *Summary Assessment on Streetcar Propulsion Technology,* attached as Section A, additional supporting information is presented in Sections B-D

Attachments include the following:

1. Section A: Summary Assessment on Streetcar Technology, July 2014 – This report summarizes DDOT's findings regarding off-wire streetcar technologies and responds directly to the requirements of the Transportation Infrastructure Amendment Act of 2010.
2. Section B: Wireless Operation in the District of Columbia, October 2011 – This summarizes a previous research effort conducted under DDOT's direction.
3. Section C: Wireless Streetcar Applications for the District of Columbia Presentation, March, 2013 – A summary presentation provided to the Mayor's Streetcar Finance and Governance Task Force.
4. Section D: Alternatives Analysis for Premium Transit Service PROPULSION STUDY, September 2013 appendices:
    a) Appendix A – Data Collection Module
    b) Appendix B – Technical / Informative Sessions with Car Builders

Section D incorporates several other studies and reviews from various sources including consulting firms, manufacturers' marketing materials, research papers and presentations from Transportation Research Board (TRB) and American Public Transportation Association (APTA) conferences. Most of these studies/reports focus on the description, analysis and applicability of various off wire propulsion technologies including On-Board Energy Storage Systems and Ground Level Power Systems. Several reports provide a review and feasibility of proprietary systems such as Primove, Innorail, TramWave and ATS.

SECTION A

Summary Assessment on Streetcar Propulsion Technology

July 2014

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Summary Assessment

on Streetcar Propulsion Technology

For

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By

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1.0 Advances in Propulsion Technology

Catenary-free or off-wire or wireless propulsion technologies can be grouped into two main categories: On-Board Energy Storage Systems (OESS) and Ground Level Power Supply Systems (GLPSS). These two systems and the individual technologies therein are described below:

1.1. On-Board Energy Storage Systems

Vehicles using this technology are powered by batteries, supercapacitors, flywheels, fuel cells, diesel and/or alternative fuel sources or a combination of these systems.

a. Supercapacitors

Supercapacitors, or double-layer capacitors, store their energy electrically in an electrostatic field. They are used to increase regeneration and lower energy consumption and are also used for off-wire operation. Supercapacitors have been installed on streetcar vehicles in revenue service by almost all major international streetcar builders. For instance, the Spanish firm Construcciones y Auxiliar de Ferrocarriles SA (CAF) initially supplied vehicles with supercapacitors for off-wire operation to Seville in 2010 to accommodate a religious procession where overhead wires would have interfered. Subsequently, CAF supplied off-wire vehicles to Zaragoza, Spain in 2011, and won additional orders for Granada, Spain in 2010 and Kaoshiung, Taiwan in 2012. SIEMENS offers supercapacitors as part of their standard Mobile Energy Storage (MES) designed to fit on the roof of any vehicle.

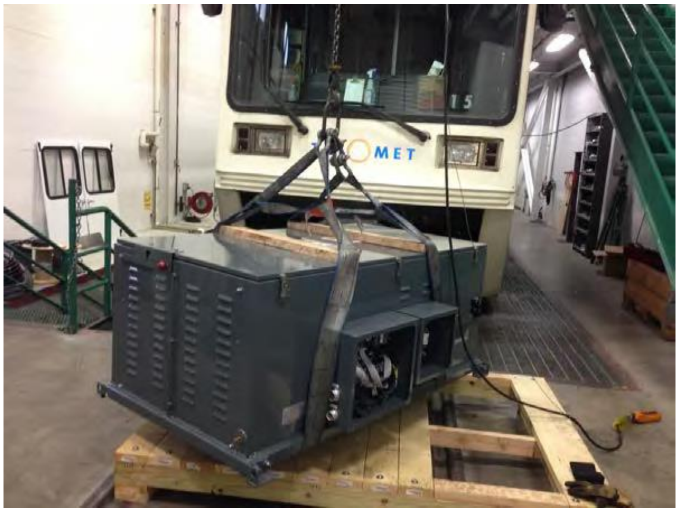

Figure 1 - Supercapacitor Energy Storage Unit being installed at Tri-Met in Portland, OR

In the United States, a demonstration project funded by a USDOT's TIGER III grant is being conducted by Tri-Met in Portland, Oregon. Supercapacitor banks from American Maglev Technologies are being fitted to 20 SIEMENS LRVs, which will operate in revenue service. The supercapacitor system charging/discharging rate is very fast, measured in seconds, and they can withstand repeated charge/discharge cycling without significant degradation over time.Design life does vary somewhat depending on the degree of cycling, but has been claimed to be on the order of 23 to 30 years.

b. Batteries

Batteries have been installed on streetcar vehicles in revenue service since mid-1800s, which predates the use of an overhead contact wire. Batteries are the most diverse type of on-board energy storage and include lead-acid, nickel-metal hydride, and, lithium-ion (Li) batteries.

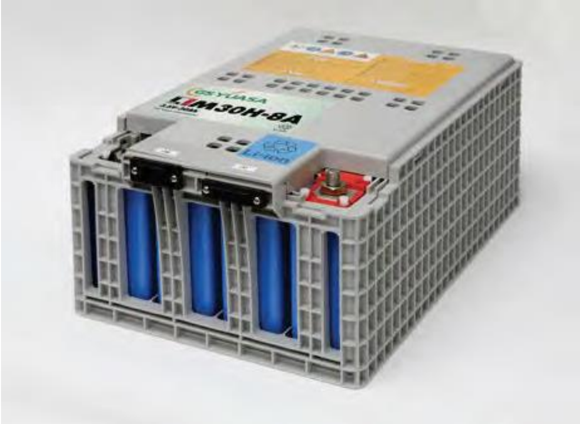

Figure 2 - Li Battery by Kinki Sharyo for ameriTRAM LRV prototype

Stadler Rail has demonstrated operation of a Li-battery equipped streetcar in Munich, Germany and the local transit authority has ordered four of the streetcar vehicles.

In the United States, Kinki Sharyo has built a demonstrator prototype, the ameriTRAM, which has toured several cities. Inekon of the Czech Republic is supplying Seatle with six “Buy America” qualified streetcars with off-wire running technology based on Li-batteries and Brookville Equipment Corporation of Pennsylvania is supplying Dallas with two Liberty streetcars with Li-batteries. Since the 1990s, San Francisco MUNI has been using NiCad batteries to power an Emergency Propulsion Unit (EPU) used to move electric trolleybuses off-wire around road obstacles and also to maneuver the trolleybuses in their parking and maintenance facility. The EPU is a high voltage battery pack consisting of 163 cells mounted on the roof of the vehicle. Rail vehicles with longer distance operability using NiMH batteries were placed into service in Nice, France, in 2007.

Figure 3 – ALSTOM Streetcar in Nice, France

The requirement of a chemical reaction results in a longer time to charge and discharge the battery, with charging usually measured in hours. However, batteries can store more energy per unit weight than other on-board storage devices like supercapacitors and flywheels. For long distances, off-wire batteries are far superior to either supercapacitors or flywheels. The slow discharge rate usually results in a lower vehicle acceleration and overall performance.

c. Flywheels

Flywheels store kinetic energy in a high speed rotating drum which forms the rotor of a motor generator. When surplus electrical energy is available it speeds up the drum, storing more kinetic energy. When electrical energy is required, the drum gives up some of its kinetic energy by driving the generator. The Parry People Mover Ltd. (PPM) in England, which has built 12 units for demonstration, uses flywheel technology. ALSTOM also continues to prototype flywheel-equipped Citadis vehicles, but has not yet marketed a model for revenue service operation. The amount of energy that can be stored in a flywheel is comparable to its electrical equivalent, supercapacitors. While future developments may result in attractive technology, flywheels are not ready for streetcars in revenue service applications.

d. Fuel Tanks (Fuel/Electric Hybrids)

Storing energy on board the vehicle to power an engine is common for buses. Compressed Natural Gas (CNG) is a mature technology for buses, but has had minimal success. Three vehicles in Nordhausen, Germany were outfitted with a diesel engine and fuel tank inside the passenger compartment. Adapting this technology to modern low floor streetcars based on electric drive technology is difficult and not cost-effective. Fuel tanks have had no significant streetcar application.

e. Fuel Cells

Fuel cells directly convert fuel to electrical power without the need for an engine or turbine. There are several demonstration projects with electric buses, and 10 prototypes are currently in revenue service at AC Transit in Oakland, CA. The prototypes are using proton exchange membrane (PEM) cells powered by hydrogen or methanol, with hydrogen getting the most interest. The buses use the fuel cells to drive electric motors as well as to charge batteries, which then can assist the electric drives. Almost all work on this technology has been performed on buses with no known applications to streetcars.

1.2. Ground Level Power Supply Systems

These systems distribute power to the vehicle via induction using the ground level power sources. These proprietary systems include APS by ALSTOM, Ansaldo’s TramWave and Bombardier’s PRIMOVE.

a. Non-Contact Inductive Power Transfer (PRIMOVE by Bombardier)

Bombardier has developed PRIMOVE - a ground level, off-wire power system which uses non-contact inductive power transfer in combination with the ‘Flexity’ model tram equipped with an ultra-capacitor energy storage system on the vehicle. The PRIMOVE application uses ground power supply by installing electrical hardware for contactless induction and relies on an electromagnetic field formed between the third rail and a magnet on the vehicle to provide electrical power to the vehicle. When a ground level segment is energized, a 20 kHz, three-phase magnetic field is created. Trains are equipped with pickup coils to receive this energy, which they convert into an electrical current that powers the tram. Transfer of energy is restricted by the distance between the vehicle-mounted collector and in-ground conductor and supplemented by the on-board ultra-capacitor system when needed. Charging of the ultra-capacitor can occur during regenerative braking or during period of light power demand, such as when coasting. The in-ground conductor is switched such that it is only energized when a vehicle occupies the segment underneath the vehicle and is non-powered at all other times. Because the system is contact-less, the vehicle is able to operate in all climates regardless of snow, ice, sand and salt on the rails.The initial testing of the PRIMOVE system began at the Bombardier facility in Bautzen, Germany in 2009 and testing on the streets of Augsburg was completed in 2012. Montreal is expected to begin testing at the end of 2013; the Mannheim test is expected to begin in the second quarter of 2014. Bombardier was recently awarded a contract in China for the construction of the first catenary-free system of its kind in that country, but revenue operations are not expected to begin until 2015-2016.

b. Surface Mounted Contact Rail - APS by ALSTOM

The ALSTOM APS proprietary system uses an in-ground contact power-rail (third rail) installed between the running rails to distribute power, and a shoe power collector installed on the vehicle. Electrical power is transmitted to the vehicle as the shoe collector makes contact with the power-rail. A loop detector installed on the vehicle allows only those segments of power-rail directly below the vehicle to be energized, thereby minimizing the risk for accidental contact between an electrified power-rail segment and pedestrians or any other objects. In the APS system the lengths of the conductor/insulator rail segments are matched to the length of the streetcar. The lengths are set such that two adjacent active segments, followed by an inactive section at each end, are always covered by the streetcar. The APS system has been in revenue operations for over 10 years in Bordeaux, France. APS is also now in use as part of the tram systems in French cities including Tours, Orleans, Angers, Nice, and Reims. The APS has been used in areas with snow, but road salt is not used for de-icing; a biodegradable deicing fluid is used instead. The APS cannot operate when covered with water.

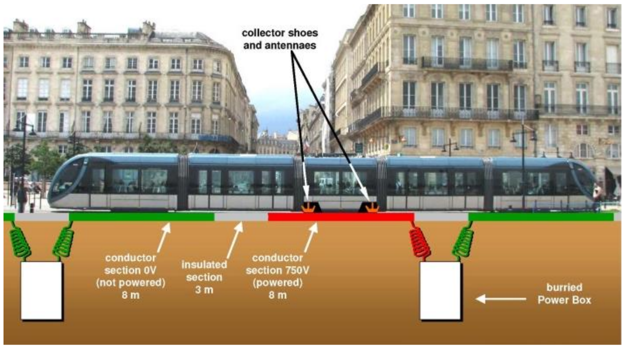

Figure 4 - ALSTOM APS System Components

c. TramWave by Ansaldo STS

Ansaldo STS' TramWave System uses a continuous conduit duct embedded in the ground running between the rails. Power is provided by segmented, insulated conductor strips ranging between 3 and 5 meters in length with each segment activated as the train passes overhead to be powered. A ferromagnetic belt in the conduit lets electricity flow to the streetcar when contact is made with the power collector shoe. Gravity causes the magnetic belt to fall back into place once a train passes by, thereby cutting off the power supply. TramWave can be installed on a variety of vehicles, and can be integrated with traditional catenary lines. All active elements of the system are fully modularized, and can be fitted to various types of track installation, including ballasted track.

The track modules also contain a return conductor instead of using the running rails as the return path. This can have substantial benefits by eliminating concerns over the corrosive effects of stray dc currents on underground utilities. The system is covered by several worldwide patents, but Ansaldo STS advertises the TramWave system as being able to fit almost any light rail vehicle or streetcar.

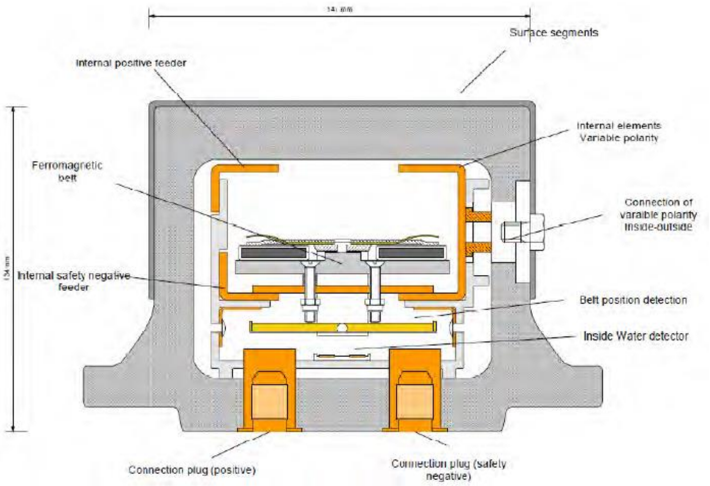
141 mm
Surface segments
Internal positive feeder
Internal elements Variable polarity
Ferromagnetic belt
Connection of varaible polarity inside-outside
134 mm
Internal safety negative feeder
Belt position detection
Inside Water detector
Connection plug (positive)
Connection plug (safety negative)

Figure 5 – Ansaldo STS TramWave – Power Rail Cross Section

1.3. Analysis and Evaluation

a. Technology Limitations

While the technologies described above have in some applications been successfully operated, the current applications are limited by the state of proven technology and environmental factors. While OESS are operating around the world, the actual demonstrated distances of operations as well as the operating conditions seem to indicate that the technology may be a considerable ways from being able to provide a completely or even substantially off-wire system in the District. Current applications are often operating over limited distances, in moderate climates, on moderate or no grades and in dedicated rights-of-way. The extended distances sought along with the District's environment, which includes occasionally harsh winters and summers, varying grades, operations in high-volume mixed traffic and high passenger demand, likely exceed the state of current OESS technology.

GLPSS options also face constraints and current operations are somewhat limited when compared to the extensive amount of off-wire operations the District eventually hopes to achieve. While topography is less of an issue for these technologies, climate can be a challenge, particularly for exposed (contact surface) GLPSS options, and some systems cannot operate when covered in water. Induction (non-contact) based systems are generally not affected by weather conditions. While the operating technologies contain technology-based safety features and have proven safe to date, some may raise safety questions, particularly in the context of exposed/contact surface GLPSS in mixed traffic. Current applications of modern GLPSS are limited and the technology is its early stages. A final issue with most if not all GLPSS systems is that they involve proprietary infrastructure components, essentially locking the end user into a single supplier, thus eliminating competition in vehicle sourcing well into the future. While specific OESS vehicle technologies may also be proprietary, the proprietary features are generally confined to the OESS components themselves. OESS vehicles in most cases can operate on a wide variety of track infrastructure.

b. Future Development

The interest in off-wire streetcars continues to grow. Most cities would prefer to be able to operate streetcars in a wire-free environment. As such, it is anticipated that this ever-increasing market demand will prompt a good deal of innovation by incentivizing manufacturers' investment in research and development and introducing economies of scale. In keeping with industry in general, at a minimum one would expect that the batteries will become more efficient, smaller in size, and lighter weight. This will permit the streetcars to remain powered and off-wire for a longer period of time, thereby providing the ability to reduce the use of overhead wire over time.

c.Buy America Considerations

This general discussion covers the state of technology currently available in the global marketplace. It should be noted that the DC Streetcar system will be subject to federal Buy America provisions. Although neither has entered revenue operations, there are currently two manufacturers supplying vehicles with some level of off-wire capability that meet Buy America requirements: Brookeville Electric Equipment (BEC) and Inekon (partnered with Pacific Marine). While several of the other manufacturers have expressed interest and the potential capability to deliver off-wire cars that meet Buy America, Inekon and BEC remain the only two companies to have taken orders for such vehicles.

d.Approach

At this time, off-wire streetcar technology remains largely in a developmental stage. While off-wire vehicles have been implemented successfully in limited applications, the various technologies have not proven capable of providing an reliable off-wire system for the entirety of the DC Streetcar system within the District's operating environment. Nonetheless, a certain amount of off-wire operations does seem feasible. Among GLPSS, the non-contact surface rail system transferring power by induction eliminates several issues seen with the contact surface rails and is the most advanced among the ground level power supply systems. With further proven applications of the technology and if the proprietary and Buy America issues can be addressed, non-contact GLPSS may prove a viable alternative at some point the future. Perhaps a more likely alternative in the near term is a hybrid system that combines some level of on-wire (OCS) and off-wire operations. The most likely scenario may be hybrid OCS/OESS vehicles with a combination of batteries and supercapacitors. It is difficult to determine at this stage the precise extent of off-wire operations that could be attainable using this approach. In addition to hybrid OCS/OESS options, hybrid OCS/GLPSS options may also provide promise for implementing these relatively new and proprietary technologies.

While the District seeks innovative solutions to minimize and possibly eventually eliminate OCS in the areas within the original L'Enfant Plan, it must be mindful to only consider solutions that can also provide operational reliability and safety while also providing responsible stewardship over District resources by maintaining reasonable life cycle costs. Balancing these considerations is critical to ensuring that DDOT provides this vitally needed transportation service while also being sensitive to the unique context of our nation's capital. In order to achieve this end, DDOT is proceeding with a consolidated design-build-operate-maintain (DBOM) delivery method for an integrated premium transit system (IPT) which includes the 22-mile Priority Streetcar System (PSS). By utilizing the DBOM approach, DDOT will be seeking a development partner that can best meet the District's varied performance goals for the system. DDOT has issued a request for qualifications (RFQ) for transit teams to deliver the system through a DBOM contract. The outcome of the RFQ will be the selection of short-listed proponents, industry leaders who will ultimately bid on providing a coordinated IPT system. The DBOM contract, while including technical specifications, will focus on performance requirements over more prescriptive specifications in order to allow the industry the level of flexibility needed to bring the highest level of innovation and partnership. Through the RFP development and industry review process, DDOT will gain critical input from the prospective bidders and utilize this input to inform the development of the final performance requirements included in the final RFP. In addition to pushing the industry to maximize the amount of off-wire operations in initial years of revenue service, the RFP will instruct bidders to also outline a plan for expanding off-wire operations as technology and circumstances permit going forward.

2.0 Feasibility, including cost, of converting to non-aerial motive power where aerial wiring has been installed

Two segments of the proposed DC Streetcar System are at or near completion for passenger service.

a. **H Street / Benning Road Streetcar Segment**, ~2.4 miles total length; ~5.0 miles of aerial OCS, 3 high-voltage traction power substations.

b. **Anacostia Initial Line Streetcar Segment**, ~1.0 mile total length, ~ 1.5 miles of aerial OCS, 2 low-voltage traction power substations.

Each segment utilizes aerial-motive power or an overhead contact system (OCS) which includes traction power substations (TPSS) and an overhead contact wire for the delivery of 750dc volts of power to the streetcars through a pantograph. The TPSS supply the 750dc volts of power to the OCS at specific locations through the use of feeder cables mechanically connected to the overhead contact wire. The TPSS are fed primary electrical power by means of low-voltage and high-voltage electricity from Pepco. The use of low or high voltage is dependent upon the proximity of the available power from Pepco, the distances between traction power substations, and the demand of the streetcar segment. The TPSS then convert the primary electrical power to 750dc volts and distribute the power to the OCS through the feeder cables to the overhead contact wire. The negative return current travels through the running rail to the TPSS through a series of rail-to-rail and track-to-track cables at prescribed locations for an efficient electrical circuit.

There are two options to consider when determining the feasibility of converting to a non-aerial power delivery system where aerial-power delivery systems are in place.

i. *Existing aerial power delivery systems remain in place.* In this scenario, the existing poles, OCS and TPSS will remain in place so that there is no associated cost of demolition and/or removal. The cost of conversion from OCS to the new technology can be divided into the following components:

    a. **For OESS (Batteries and/or Supercapacitors Technology)** – The cost of the new vehicles including the batteries, supercapacitors and charging stations will be the added cost.

This is assuming that the streetcar tracks, physical stops and signage items are unchanged between the two technologies. It is also possible that the TPSS can be repurposed to serve as charging stations. It would be required to retrofit the streetcar stations to provide charging capabilities. A high-level estimate of the costs breaks down as follows:

i. Vehicles (including spares) –
   1. Cost Range of a Baseline Streetcar Vehicle:
      a. Low - $5million
      b. High - $7million
   2. Cost factor for adding batteries/supercapacitors:
      a. Low – 10% of baseline cost
      b. High – 30% of baseline cost

ii. Retrofit/install charging stations – In order to reasonably estimate the potential cost to install charging stations or retrofit existing streetcar platforms to accommodate a charging station the proprietary model of vehicle, battery, and/or super capacitor should be identified. The most economical cost approach is when the existing aerial power delivery system (OCS) remains in place and is utilized to recharge batteries or super capacitors. A typical streetcar platform with shelters, pylons, and furnishings is approximately $300,000 each to construct in the District's public space. Any additional facility needed for charging stations would be in addition to the $300,000 baseline cost.

Technical feasibility – As discussed above, on-board energy storage technologies have limitations with the amount of energy that can be stored on the vehicle versus the amount of energy required to operate across a wireless area. Operation in mixed traffic lanes is particularly difficult to estimate as unpredictable but normal events such as an unusually high traffic volume, traffic accident or diplomatic motorcade can extend the time off-wire and exhaust the stored energy before it returns to a charging location or powered track, thereby stranding the vehicle. Topography places additional limits on on-board energy storage systems, as challenging grades exhaust the power supply much more quickly.

b. **For GLPSS (including contact and non-contact systems)** – This system requires the installation of in-ground electrical hardware in combination with the specialized vehicle equipped with power receiver system, an ultra capacitor energy storage system, and vehicle detection and segment control antenna to energize the wayside power cable segment. This is a proprietary system and the costs are not known at this time. However, the installation of this system would require that the existing rail tracks are removed to install the new power cables, vehicle detection and segment control cables, high-voltage inverters, and supervisory control and data acquisition interface for the new in-ground system before the tracks can be reinstalled. The presence of poles, OCS and TPSS may not cause any hindrance; however that remains to be confirmed.

It is important to note that this system is very new and has not been used in revenue service thus far. The current applications are limited to controlled demonstration lines on dedicated right-of-way only. The transference of energy from the wayside to the vehicle depends on maintaining a small gap between the vehicle's collector and the supply rail which may restrict the vertical curve capabilities in areas such as underpasses. Installation and protection of in-street high voltage contactor boxes at frequent intervals is required. The pre-formed rail assemblies are proprietary and available only from a sole supplier.

i. Vehicles (including spares) –
    1. Cost Range of a baseline Streetcar Vehicle:
        a. Low - $5million
        b. High - $7million
    2. Cost factor for specialized vehicle equipped with power receiver system:
        a. Low – 20% of baseline cost
        b. High – 40% of baseline cost

ii. Existing embedded concrete track & special trackwork demolition:
    1. $120 per track foot
    2. H/Benning is ~25550 track feet = ~$3.06 million

3. Anacostia is ~7880 track feet = ~$950,000

iii. Replacing embedded concrete track (without proprietary conductor rail):

1. $581 per track foot
2. H/Benning is ~25500 track feet = ~$14.80million
3. Anacostia is ~7880 track feet = ~$4.60million
4. Cost factor for proprietary conductor rail = Undetermined
    a. Labor and equipment to install is assumed or considered to be similar and equivalent to conventional reinforced concrete embedded track installation.
    b. Material cost for proprietary conductor rail is not quantifiable. As the technology is unique to the manufacturer and public information is not available, it is not practical to estimate the costs for these items. In addition to the basic materials that comprise the technology, the research and development costs as well as manufacturing start-up costs for a new technology would need to be recovered by the owner of the technology.

iv. Replacing embedded concrete special trackwork (without proprietary conductor rail):

1. $60,000 per each turnout
2. H/Benning's 11 turnouts = ~$660,000
3. Anacostia's 6 turnouts = ~$360,000
4. Cost factor for proprietary conductor rail = Undetermined
    a. Labor and equipment to install is assumed or considered to be similar and equivalent to conventional reinforced concrete embedded track installation.

b. Material cost for proprietary conductor rail is not quantifiable. As the technology is unique to the manufacturer and public information is not available, it is not practical to estimate the costs for these items. In addition to the basic materials that comprise the technology, the research and development costs as well as manufacturing start-up costs for a new technology would need to be recovered by the owner of the technology.

ii. *Removing aerial power delivery systems including OCS and TPSS.* Street lighting and traffic signal infrastructure has been designed to be accommodated on OCS poles in effort to limit the visual impact poles and wires. If the aerial power delivery system was deconstructed, the existing street lighting and traffic signal infrastructure may have to be reconstructed as well.

a. **For Batteries+Supercapacitors Technology** – The cost of removal of the poles and OCS will be a marginal expense in addition to the costs estimated above.

   i. Remove, salvage, & demolish OCS wire, OCS Poles, OCS Hardware, & foundation:

      1. $30 per track foot
      2. H/Benning is ~25550 track feet = ~$765,000
      3. Anacostia is ~7880 track feet = ~$236,000

   ii. Remove, salvage, decommission & restore Traction Power Substations:

      1. ~$200,000 per tpss unit
      2. H/Benning's 3 TPSS units = ~$600,000
      3. Anacostia's 2 TPSS units = ~$400,000

   iii. Loss of initial investment: The District has invested approximately ~$22 million dollars cumulatively in the OCS, traction power substations, and train control system that makes up the aerial power delivery system on the H/Benning Segment. This includes the mainline and operation/maintenance facility.

b. **For Ground Level Induction System** – The cost of removal of the poles and OCS will be a marginal expense in addition to the costs of the proprietary system discussed above.

   i. Remove, salvage, and demolish OCS wire, OCS Poles, OCS Hardware, and foundation:

      1. $30 per track foot
      2. H/Benning is ~25550 track feet = ~$765,000
      3. Anacostia is ~7880 track feet = ~$236,000

   ii. Remove, salvage, decommission & restore Traction Power Substations:

      1. ~$200,000 per tpss unit
      2. H/Benning's 3 TPSS units = ~$600,000
      3. Anacostia's 2 TPSS units = ~$400,000

   iii. Loss of initial investment: The District has invested approximately ~$7 million dollars cumulatively in the OCS, traction power substations, and train control system that makes up the aerial power delivery system on the Anacostia Initial Segment. This includes the mainline and operation/maintenance facility.

3.0 Feasibility, including cost, of using non-aerial motive power on such segments of the streetcar system where construction has yet to be initiated

a. **For Batteries+Supercapacitors Technology** – The cost of installing the tracks, relocation of utilities, and the construction of streetcar stops can be estimated from the recent H/Benning and Anacostia Initial Line segments. The cost of the new vehicles including the batteries, supercapacitors and charging stations will be the added cost. Additionally, on-board energy storage technologies have limitations with the amount of energy that can be stored on the vehicle versus the amount of energy required to operate across a wireless area. Operation in mixed traffic lanes is particularly difficult to estimate due to unpredictable but normal events, such as an unusually high traffic volume, traffic accident or diplomatic motorcade, which can extend the time off-wire and exhaust the stored energy before it returns to a charging location or powered track, thereby stranding the vehicle.

b. **For Ground Level Induction System** –The cost of installing the tracks, relocation of utilities, and the construction of streetcar stops can be estimated from the recent H/Benning and Anacostia Initial Line segments. The ground-level induction system requires the installation of in-ground electrical hardware in combination with the specialized vehicle equipped with power receiver system, an ultra capacitor energy storage system, and vehicle detection and segment control antenna to energize the wayside power cable segment. This is a proprietary system and the costs are not known at this time. However, the installation of this system would require that the existing rail tracks are removed to install the new power cables, vehicle detection and segment control cables, high-voltage inverters, and supervisory control and data acquisition interface for the new in-ground system before the tracks can be reinstalled.

   It is important to note that this system is very new and has not yet been used in revenue service. The current applications are limited to controlled demonstration lines on dedicated right-of-way only. The transference of energy from the wayside to the vehicle depends on maintaining a small gap between the vehicle's collector and the supply rail, which may restrict the vertical curve capabilities in areas such as underpasses. Installation and protection of in-street high voltage contactor boxes at frequent intervals is required. The pre-formed rail assemblies are proprietary and available only from a sole supplier.

4.0 Any recommended amendments to this act, including a potential sunset date

After engaging in a multi-year rigorous public involvement process and collaboration with key stakeholders on streetcar, DDOT continues to seek to implement innovative solutions to minimize and possibly eliminate OCS in the areas within the original L'Enfant Plan. DDOT seeks solutions that will provide both operational reliability and safety while at the same time providing responsible stewardship over District resources. Streetcars have had a long history in the District and operated with the overhead wires in the District for nearly 100 years. The return of streetcars will accommodate growth, enhance mobility, provide Metrorail core capacity relief, and support economic development. DDOT will work with the Council as the streetcar program moves forward to identify any potential amendments to the act.

SECTION B

Wireless Operation in the District of Columbia

October, 2011

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District Department of Transportation

Wireless Operation in the District of Columbia

October 2011

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Wireless Trolley Operation in the District of Columbia

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INTRODUCTION

In the early 20th century, the transition from horse-drawn trolleys to self-propelled trolleys, or streetcars, required the development of a means to provide a constant source of power to the vehicles. Early efforts consisted of engine-driven vehicles powered by steam or fossil fuels which quickly fell out of favor due to the attendant noise and exhaust vapors. Electrically-powered vehicles replaced their predecessors with the development of power delivery systems both in the ground and suspended safely from aerial wires. Eventually, the overhead contact wire technology gained widespread acceptance. The wires were suspended from poles with cantilevered wire attachments or span wires attached to a pair of poles on opposite sides of the street. In some instances the span wires were attached directly to buildings adjacent to the alignment. The photographs in Figures 1-4 illustrate the different methods used to support the contact wire over the streetcar tracks.

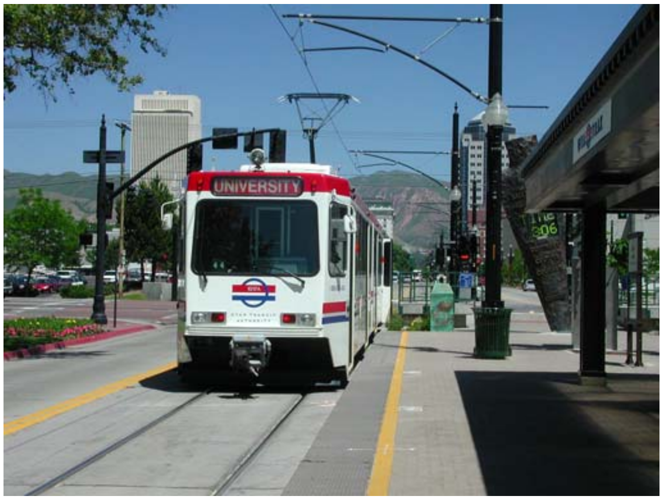

Fig. 1 - Side Cantilevered Support Arms (Salt Lake City, UT)

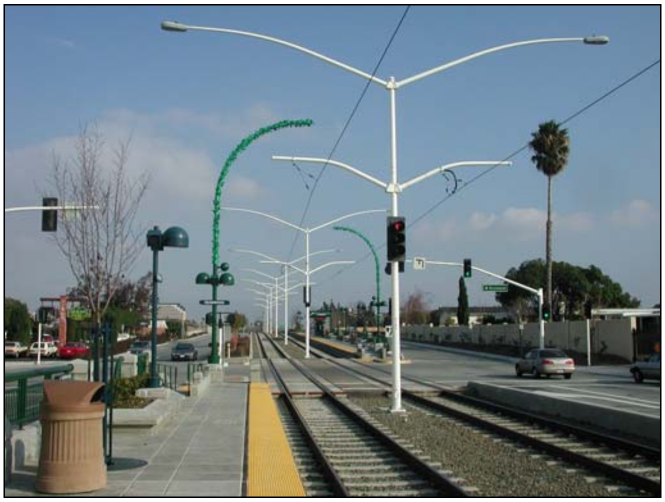

Fig. 2 - Joint-use Center Cantilevered Supports (San Jose, CA)

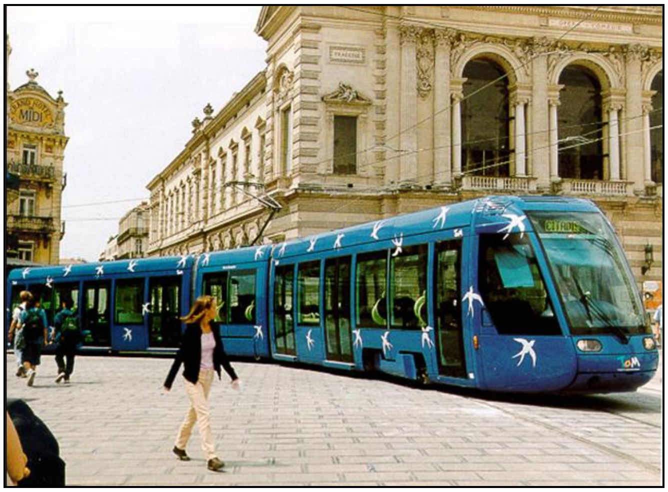

Fig. 3 - Span Wire Support (Montpellier, France)

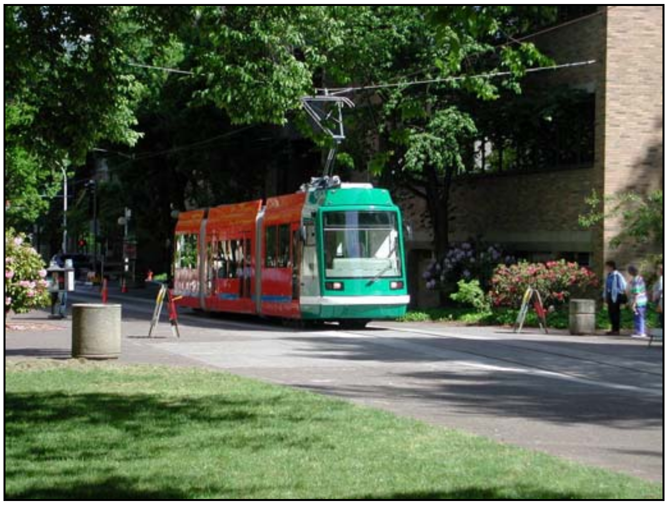

Fig. 4 - Building Attachment (Portland, OR)

Many cities have rich histories that continue to live in the form of monuments, classic buildings and treasured open spaces. It is the desire of these city leaders to maintain the site lines and view corridors for all to enjoy. In order for streetcar lines to introduce minimal visual obtrusiveness with these historical structures and open spaces, it is desirable to deliver power through means other than using overhead wires. The District of Columbia is a perfect example, where all utilities are buried, and site lines and/or view corridors are established to preserve the architectural features of the landscape. Introducing poles and overhead wires as part of a new urban streetcar project is naturally met with resistance. Some cities have taken advantage of, or are experimenting with, new technologies that will allow streetcars to operate through these view-sensitive areas without any overhead wire system.

This report provides an historical background for Washington, DC and an overview of current technologies in use or being developed, which may be utilized to continue the wireless tradition.

ALTERNATIVES IDENTIFICATION

The technologies substituting for overhead wire can be placed into three categories:

- Wayside Technology: those which are installed on the wayside and deliver power to the streetcars by means other than overhead wire;

- Onboard Energy Storage Technology: those which employ energy storage devices on the streetcars; and
- Onboard Power Source Technology: those which serve as an onboard power source.

Wayside Technologies

Wayside technologies include those applications by which electric power is brought to the vehicle by some means at or beneath the street level. These include conventional overhead contact wire systems, the District's earlier system using sub-surface conduit rail, surface-mounted contact rail, and non-contact inductive power.

Sub-Surface Conduit Rail

The conduit rail system is not a currently deployed technology. It is described here as an historical reference because it did address a similar challenge in a previous era and the operation of the system can provide lessons for the application of new systems. The basic system was employed as early as 1895 in New York City and Washington, DC, in the United States and in London, England. Although the technology was tried by several localities, only the cities listed here used this sub-surface power supply system for an extended period of time. The last of these systems was operated in the District and was decommissioned in 1962.

The conduit system utilized underground positive and negative "rails" from which power was collected by a vehicle-mounted "plow". The conductor rails were mounted on insulators attached to cast iron "yokes" positioned every 13.5 feet in Washington and 15 feet in New York. Handholes were provided to allow maintenance access to the insulators and drains installed to prevent flooding of the rail channels. The positive rail was attached to one side of the yoke and the negative rail was attached to the opposite side with a separation of about six inches. The plow extended about 16 inches below the street level through about a half-inch steel slot on the surface of the street. The yokes were installed below the street surface between the tracks and extended 38 inches below the surface of the street. Figure 5 shows a picture of the track and conduit rail in the street, while Figures 6 and 7 are drawings illustrating the conduit rail cross-section and the plow in the Washington, DC application (taken from the Electrical Engineer's Pocket Reference published in 1918).

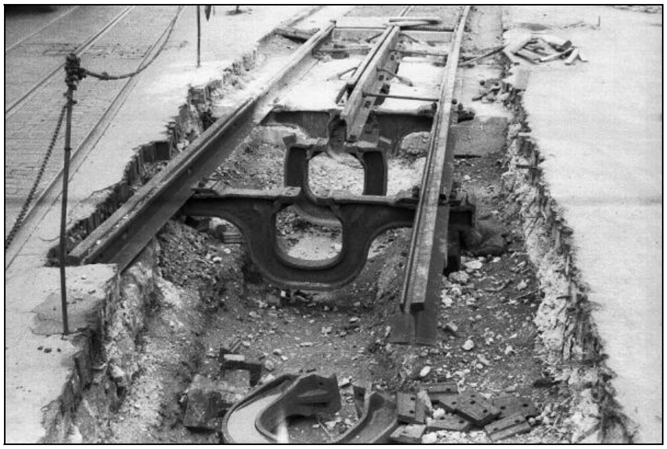

Fig. 5 - Photo of Rail in Street

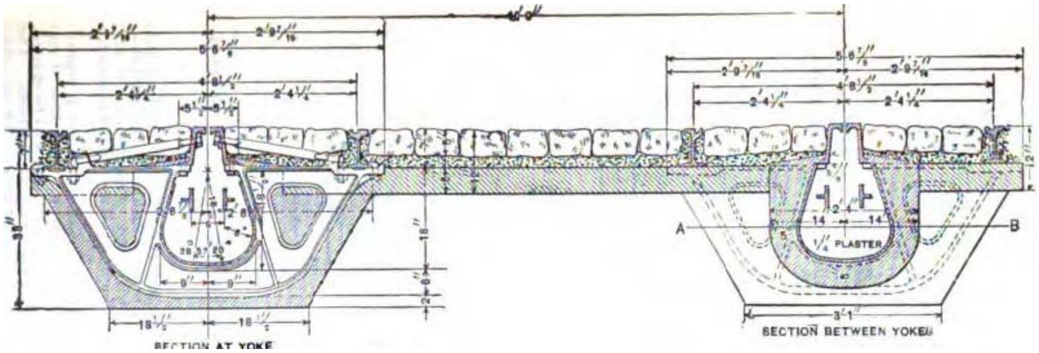

Fig. 6 - Cross-section of Conduit Rail in Washington, 1895

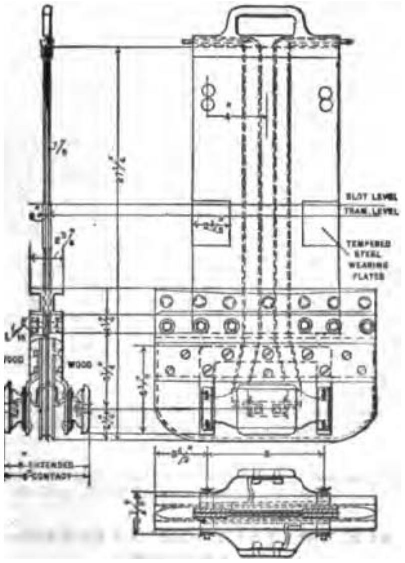

Fig. 7 - Section, Side, and End Elevation of Plow, New York, 1897/99

In Washington, DC, the streetcars were operated with a traditional trolley pole in contact with overhead wire in suburban areas and with conduit rail in the central area of the city (the old L'Enfant City) where overhead wires were banned. The changeover was accomplished by two people - one person in an underground pit to install or remove the plow and one person above to raise or lower the trolley pole. On lines with short headways, the changeover time was critical, as well as being labor intensive.

The limited number of installations of this system was primarily a result of the high construction, operating, and maintenance costs. Reliability of the system is believed to have been good despite the occasional dropped plow or frozen slot, which would cause major service disruptions, such as can be seen in Figure 8.

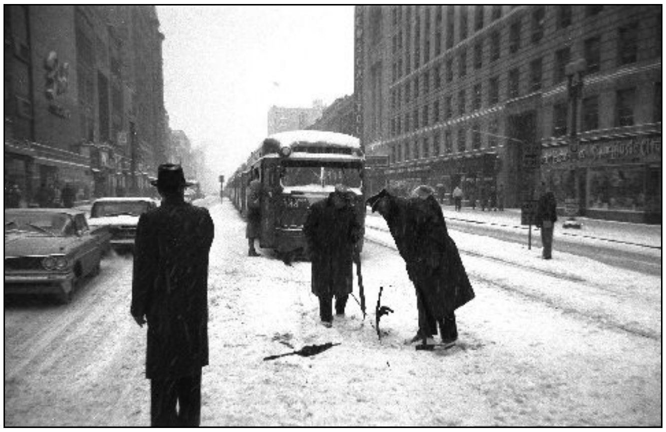

Fig. 8 - Line of Streetcars and Iced Slot

Surface Mounted Contact Rail

The delivery of power to the vehicle through an exposed conductor mounted on the surface of the street is of both historical and current interest. General Electric had a working system installed in Monte Carlo, Monaco, as early as 1898. Currently, Alstom and Ansaldo Breda have surface-mounted systems in service or in development. The Alstom system is operating in Bordeaux, Orleans, Rheims, and Angers in France, and in Dubai in the United Arab Emirates. The Breda system is presently undergoing testing at the Breda plant with plans to install this system on a portion of a streetcar line in Florence, Italy in the near future.

At the turn of the last century two US suppliers, General Electric and Westinghouse, were marketing solutions that used conductors mounted on the street surface and claiming the installation costs were one half that of an overhead conductor system. The systems were quite similar in that they both used two contact rails on the vehicle and two rows of cast iron “buttons” installed on the street surface. Two diagrams of the system, taken from the Electrical Engineer’s Pocket Reference, are shown in Figures 9 and 10.

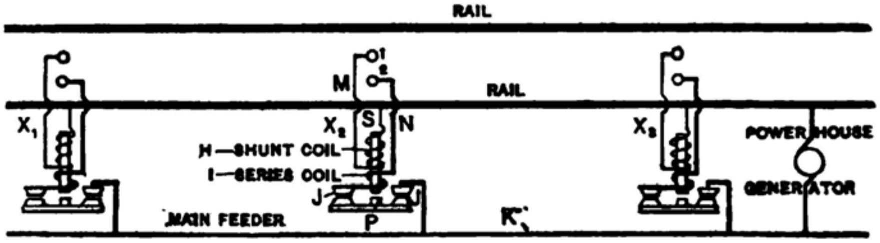

Fig. 9 - Diagram of Switch Connections

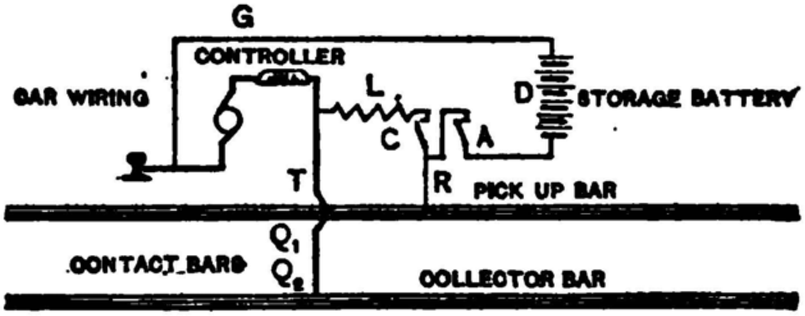

Fig. 10 - Diagram of Vehicle Connections

The buttons were connected to the power supply through electro-magnetically operated switches (Fig. 9) typically installed every 15 feet along the tracks. When a vehicle was over the buttons, a current would flow and electro-magnetically lift an armature to close the contacts that supplied power to the buttons. When the vehicle moved forward and there was no contact with the prior buttons, the armature would drop by gravity and open the circuit, de-energizing the surface-mounted buttons. This system required the establishment of two independent connections, and the force for opening the connection was provided by gravity.

Beginning In the mid-1990s, a system consisting of a magnetically-lifted power feed to contact a street-mounted rail to deliver power to the vehicle was developed by AnsaldoBreda. Originally called the STREAM system (the acronym in Italian for “magnetic pick-up electric transportation system”), the current designation is TramWave. The power collector on the vehicle was equipped with a strong magnet to lift the flexible conductor against the surface rail as the vehicle passed over it. That part of the conductor would drop with gravity when the vehicle moved past it.

The TramWave design uses a system of 19.7 inch (500 mm) plates which feed power at 750 Vdc from a positive feeder housed in a “box” mounted in the street to a collector mounted on the truck of the vehicle. Both positive and return conductors are incorporated in this arrangement, eliminating the need to use the running rails as the return path. Not using the running rails as the return path greatly reduces the need for electrical isolation of the rails and stray current mitigation issues. This concept is illustrated in Figure 11.

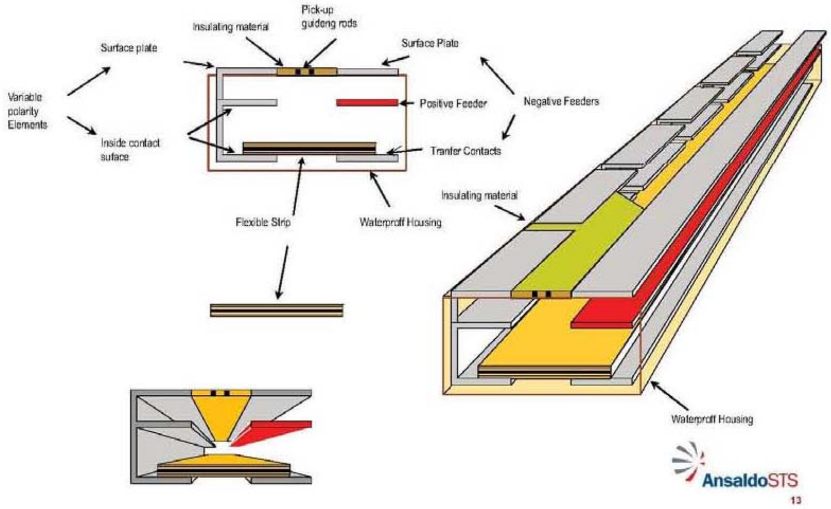

Fig. 11 - Diagram of Ansaldo Breda TramWave

This system was installed and tested on a trolley bus application in Trieste, Italy. It has also undergone some experimental testing in Naples at the Ansaldo facility. Currently a new streetcar system in Florence, Italy is planning to install the TramWave surface rail on two short sections.

As part of its new light rail system, the City of Bordeaux required that there be no overhead wire through its downtown historic district. The tender to accomplish this was won by Spie Enertrans, who had developed a unique surfaced contact system they dubbed Innorail. The system was developed in concert with Alstom Transportation who was providing the light rail vehicles. Alstom subsequently acquired the Innorail technology, made improvements to it, and renamed it APS, an acronym for Alimentation Par le Sol, which translates as ‘ground power supply’. They have also referred to is as ‘Aesthetic Power Supply’. The Bordeaux system has been in operation since 2003 and expansion of the system continues today. Despite initial start-up problems during the first year, the system has proven highly reliable.

Dramatic photographs of the rail system operating through the historic district are shown in Figures 12 and 13.

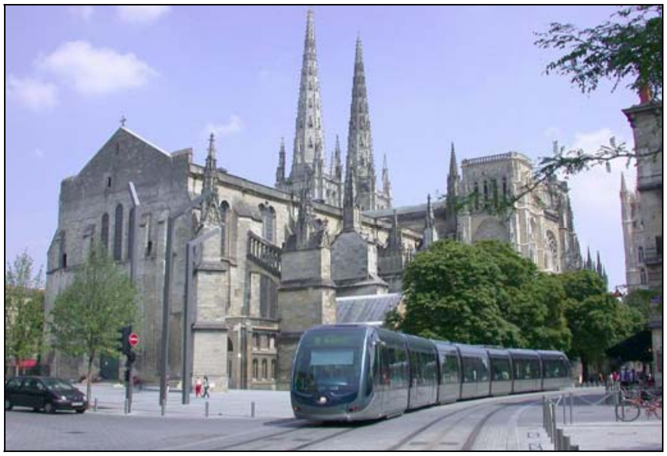

Fig. 12 - Bordeaux Wireless Operation

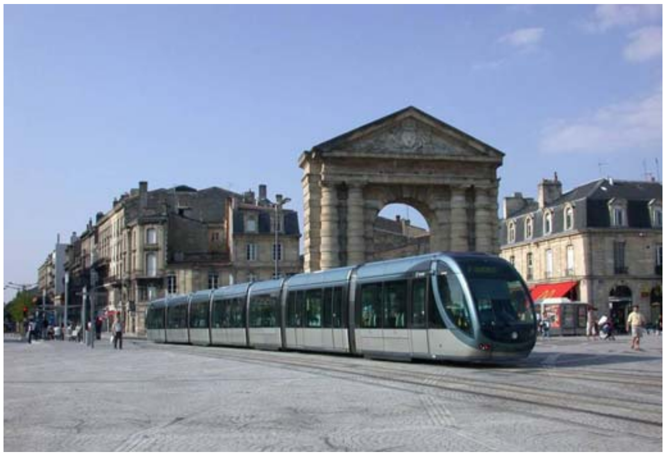

Fig. 13 - Bordeaux Wireless Operation

As shown in Figure 14, the APS system uses a segmented design with the contact bars mounted slightly above the surface of the street in the track centerline. Power conducting segments are 26½ ft (8 m) in length and are separated by insulating segments of 10 ft (3 m). Power supply boxes are located every 73 ft (22 m). Two power collector shoes are suspended from the underside of the vehicle. They are located slightly more than 10 ft (3 m) apart to bridge the insulating segment, assuring a continuous supply of power to the vehicle. The dimensions of the segments are dependent on the length of a vehicle such that two adjacent active segments, followed by an inactive section at each end, are always covered by the streetcar.

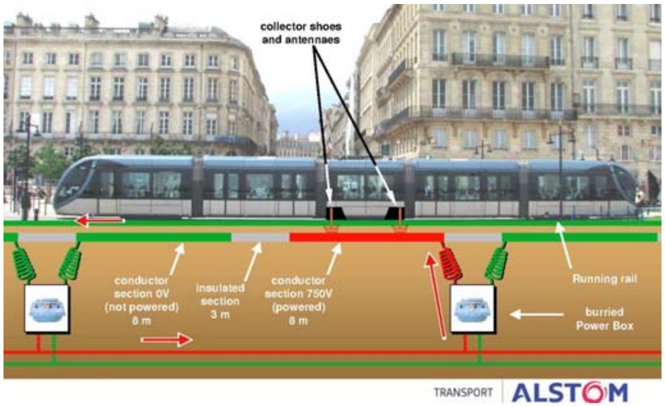
collector shoes and antennaes
conductor section 0V (not powered) 8 m
insulated section 3 m
conductor section 750V (powered) 8 m
Running rail
burried Power Box
TRANSPORT ALSTOM

Fig. 14 - Alstom Sectionalizing Diagram

The embedded structure for the contact strips is installed in a shallow tray located in the center of the tracks as shown in Figure 15. This embedded structure also contains an inductive detection loop, power supply conductors, ground conductors, and communications conductors inside individual compartments, simplifying the installation work.

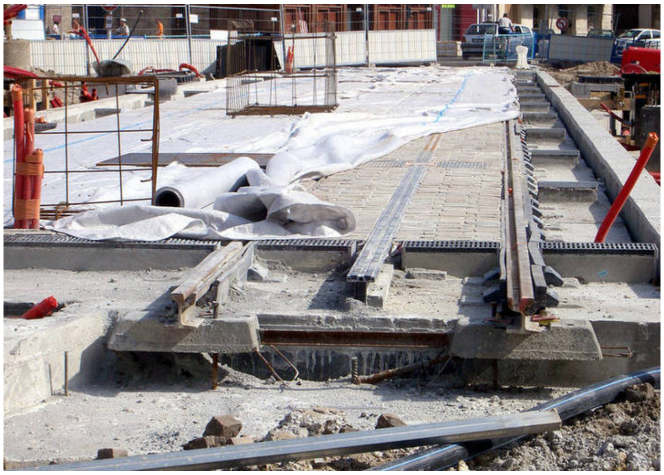

Fig. 15 - Installation of APS System

Individual segments are energized via the power boxes when the presence of a vehicle is detected by means of an inductive detection loop. Segments are switched by regular electro-mechanical contactors housed in the power boxes embedded in the street. After the vehicle's power rail shoes have passed and the inductive loop no longer detects the presence of a vehicle, the power is switched off and the rail connected to ground.

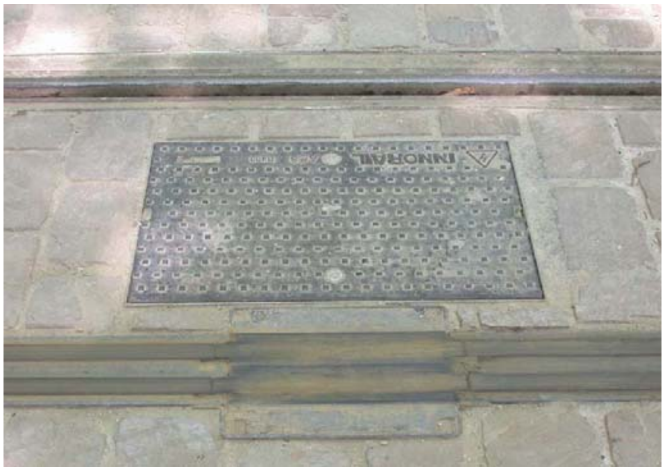

Fig. 16 - Power Box Installation

The APS system does have some drawbacks. It is currently only available from the French company, Alstom, as a proprietary design, and the willingness of Alstom to install the system in a US city is unknown. The cost differential between this system and a traditional overhead contact wire system is not precisely known, although various sources report that the APS is three to three-and-a-half times more expensive to install. The cost for the future purchase of streetcars may also be significantly more expensive, as the purchase will be “locked-in” to this carbuilder. The four French cities utilizing APS have applied it in very limited areas and over relatively short distances, typically urban historic districts, while installing overhead contact wire elsewhere on their rail networks.

Both of these surface contact systems which rely on direct contact between the vehicle-mounted shoe and the copper contact bar in the street can be anticipated to have problems with snow, ice, and corrosive de-icing chemicals. Historically winter weather has been an issue with underground rail in the District of Columbia as shown on Figure 8. For this type of system, the presence of road salt on the contact strips for an extended period of time may cause them to corrode, resulting in poor power transfer and accelerated replacement.

Non-Contact Surface Rail

A new technology is emerging which utilizes inductive transfer of power from the wayside to the vehicle through an air gap without the need for exposed conductors or physical contact. A small scale example of this is how a Sonicare toothbrush is recharged by simply setting it in its base which has no metallic contacts. An auxiliary benefit of this technology is that it uses alternating current (ac) instead of direct current (dc), which avoids the corrosive effects of stray current on nearby metallic objects such as building structures and underground utilities.

The inductive technologies have been implemented in two distinct styles. The first style uses discrete charging stations along the alignment with on-board energy storage during operation. The second style uses a continuous transfer of energy from the wayside during operation and stores a smaller amount of on-board storage for high demand activities such as streetcar acceleration or grade climbing.

An example of the discrete charging style is the battery-powered double-decker streetcar operating at The Grove, an outdoor shopping mall in the Hollywood area of Los Angeles. In addition to being recharged in the maintenance shop, the streetcar batteries are inductively recharged from power boxes embedded between the rails at station stop locations. The level of charging at station stops is dependent upon the dwell time at each station (time required for passenger are boarding and alighting). The charging station (power box) is supplied by the German company, Wampfler, which is actively promoting this technology for transit. Wampfler has also supplied an inductive power supply for a people mover at Mexico City's airport and for buses in Genoa, Italy. Electric buses using inductive charging at stations are also being prototyped by Hino in Japan and the University of Auckland, New Zealand.

Fig. 17 - Streetcar at the Grove

Bombardier, one of the world's largest suppliers of rail vehicles, is developing their 'Primove' system for continuously powering a rail car via inductive power transfer from under the street. They have recently completed a demonstration project in Bautzen, Germany, reaching speeds up to 24 mph (40 km/h) and operating on grades up to 6%, on a 0.6 mile (1 km) test track. Bombardier has recently announced receipt of an order for installation of the system on a 0.5 mile (0.85 km) line in Augsburg, Germany.

The Primove application uses a 'Flexity' model tram equipped with a 'Mitrac' ultra-capacitor energy storage system on the vehicle. The in-ground system does not utilize direct contact of the collector on the car with the rail in the street. A cable loop is installed under the pavement and energy is transferred through a magnetic field to a receiver mounted on the vehicle's truck. Transfer of energy is restricted by the distance between the vehicle-mounted collector and in-ground conductor and supplemented by the on-board ultra-capacitor system when needed. Charging of the ultra-capacitor can occur during regenerative braking or during period of light power demand such as when coasting. The in-ground conductor is switched such that it is only energized when a vehicle occupies the segment underneath the vehicle and is non-powered at all other times similar to the surface contact rail systems. An illustrative graphic from a recent Bombardier brochure is shown in Figure 18.

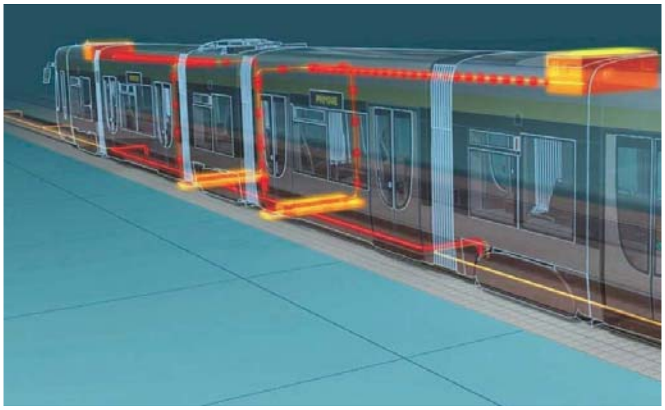

Fig. 18 - Bombardier Primove Graphic

On-Board Energy Storage

A disadvantage of the wayside power system alternatives is the need for the installation of a fixed infrastructure, to produce the same results as an overhead catenary system, but at a greater cost. A variety of different technologies used to store energy onboard vehicles to propel them without the fixed infrastructures described above, have been developed. These technologies differ in the amount of energy that can be stored and the distance the vehicles can travel before needing to replenish that energy. The energy source is either some external power supply or kinetic energy captured by the vehicle in motion and converted to electrical energy. The storage medium is either batteries or ultra-capacitors. The kinetic energy can also be stored by some mechanical device, such as a flywheel.

Batteries

The use of high-voltage battery-banks to power transit vehicles is a proven technology. The composition of batteries has evolved from the original lead-acid type to nickel-cadmium (NiCad), to nickel-metal-hydride (NiMH) and currently moving toward lithium ion (LiB) batteries. Each advancement in battery technology has resulted in a reduction of the battery weight required to store the same amount of energy. Another improvement is that the NiMH and LiB batteries do not contain either lead or cadmium.

Batteries provide the highest energy density of the electrical storage options, allowing the longest operating distance per installed weight. The most significant downside is the relatively slow charge/discharge capability and tight monitoring required. The battery charging current must be controlled so that permanent damage to the batteries does not occur. Avoiding this situation requires a separate micro-processor-controlled battery charger and cooling of the battery compartment. It also results in slower vehicle acceleration rates and top speed when operating on battery power. Newer LiB models are beginning to allow faster charge/discharge rates without a significant reduction in service life.

Batteries also need to be oversized for their intended application. To prolong battery life, it is best to keep the operating range between 20% and 80% of the total capacity. For an installed capacity of 25 kWh, this means 5 kWh must be reserved at both the lower end and the higher end, resulting in a useable capacity of 15 kWh. Additional capacity during operation could be realized using regenerative energy from braking.

Since the 1990s, San Francisco MUNI has been using NiCad batteries to power an Emergency Propulsion Unit (EPU) used to move electric trolleybuses off-wire around road obstacles and also to maneuver the trolleybuses in their parking and maintenance facility. The EPU is a high voltage battery pack consisting of 163 cells mounted on the roof of the vehicle.

The District's existing Inekon streetcars have a similar emergency power supply application using the standard on-board battery as a back-up power supply. This system only provides power at 24 Vdc and is therefore severely limited in speed and distance. Under battery power the streetcar can move at only about 2 miles per hour for 500 feet on level track. This capability is intended to allow a streetcar to clear an intersection in case of loss of overhead power on the line, and for short movements in the storage yard and maintenance facility. The NiCad batteries are installed under the car, whereas high voltage battery sets are typically installed on the roof.

Rail vehicles with longer distance operability using NiMH batteries were placed into service in Nice, France, in 2007. Nice has two historic town squares, Place Massena and Place Garibaldi, each about 0.3 miles long and where the use of overhead wire was strongly discouraged. The town squares are near the center of the 5.5-mile (8.7 km) line. Vehicles are powered by overhead wire everywhere but these two locations, where they rely on on-board battery power. Travel over the remainder of the system allows sufficient time to fully charge the batteries from the overhead wire. Figure 19 provides a photograph of one of the Nice vehicles, manufactured by Alstom, operating on an overhead wire portion of the line.

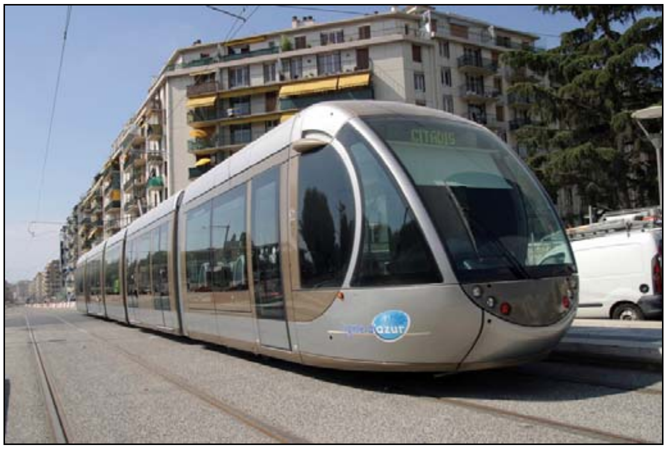

Fig. 19 - Alstom Nice Streetcar

High voltage NiMH battery sets with lesser capacity than provided for the Nice vehicle are also installed on the streetcars manufactured by Alstom that operate on the APS surface-mounted contact rail system. The batteries are required to move the vehicle over a dead section of contact rail if such is encountered. The battery systems in these vehicles are very similar to those installed on the Nice vehicles.

In 2007, the Japanese railcar supplier, Kawasaki, introduced its hybrid SWIMO ‘Smooth WIn MOver’ or SWIMO that can run on overhead wire or on-board batteries (see Figure 20). The SWIMO vehicle is shorter and narrower than many other examples of modern streetcars, measuring only 50 feet (15 m) long and 7.3 feet (2.23 m) wide. It has 28 seats and a maximum capacity of 62 passengers. Media reports claim this vehicle can travel up to 6 miles (10 km) at a top speed of 12 mph (20 km/h) on battery power alone. It has been reported that the SWIMO has been operated up to 23 miles (37 km) without recharging under test conditions. The vehicles are equipped with NiMH batteries stored under passenger seats.

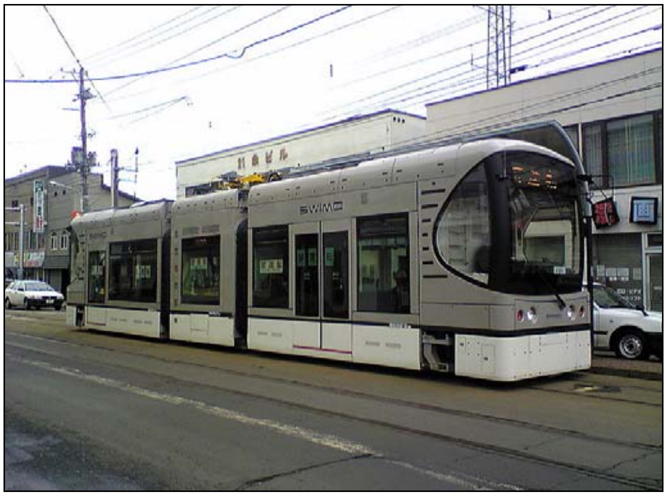

Fig. 20 - Kawasaki SWIMO streetcar

This year Kinki Sharyo unveiled their American version of the Japanese J-tram, named AmeriTram. The AmeriTram uses LiB technology and has located the batteries under the seats. The batteries are accessible for maintenance from the exterior of the car through access panels on the exterior sides of the vehicle. Because of the battery location, the car design is limited to one double-width door per side. The AmeriTram has been estimated to be capable of operating up to 3 miles (4.8 km) in revenue service during off wire operation.

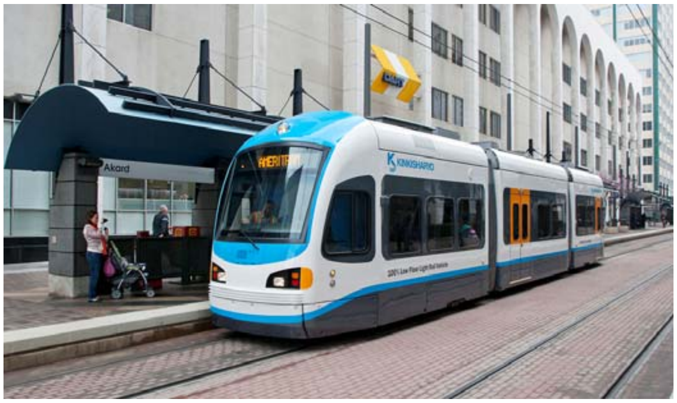

Fig. 21 – Kinki Sharyo AmeriTram

Ultra-capacitors

New technological advances have made ultra-capacitors a viable alternative for on-board energy storage, and several manufacturers are pursuing implementation on streetcars. The attraction for propulsion suppliers is the relative ease of charging and discharging compared to the tight control of current required for batteries. The downside is the lower energy density compared to batteries, which limits the travel range without intermediate recharging.

One feature of ultra-capacitor operation is that there are no chemical processes associated with the charging and discharging of the unit. This makes it effective for very rapid transfer of power such as when starting a vehicle or recovering regenerative braking energy. Without a chemical reaction, degradation of the materials is much less of a concern than with batteries. The typical construction materials are aluminum, carbon, paper, and an organic electrolyte, making it environmentally friendly.

The downside to ultra-capacitors is their low energy density and higher cost when compared to batteries. Typically, an ultracapacitor can only store 10 to 20% of the energy storable in a battery for the same unit weight. This limits the amount of energy that can be reasonably stored on a vehicle and, therefore, the distance the vehicle can travel. However, continuing advances in this technology, including the introduction of carbon nanotubes, are increasing the energy density and lowering the price of these components.

Bombardier developed a prototype on a light rail vehicle and placed it into revenue service in Mannheim, Germany. This vehicle was tested over a four-year test period ending in 2007. This vehicle uses the ultra-capacitors primarily for the recovery and storage of excess regenerative braking energy and not operation off-wire. Nonetheless, off-wire operation for the vehicle was demonstrated for a distance of up to 0.3 miles (500 m) with one start and stop. The system, known as ‘MITRAC’, is a main component of Bombardier’s environmentally-friendly initiative, EC04, announced last year. Testing of the MITRAC system is ongoing at their test track in Bautzen, Germany. Meanwhile, the transport agency in Mannheim has ordered 19 ultracapacitor-equipped light rail vehicles from Bombardier. Figure 22 illustrates the placement of the ultracapacitor assembly on the roof of the vehicle.

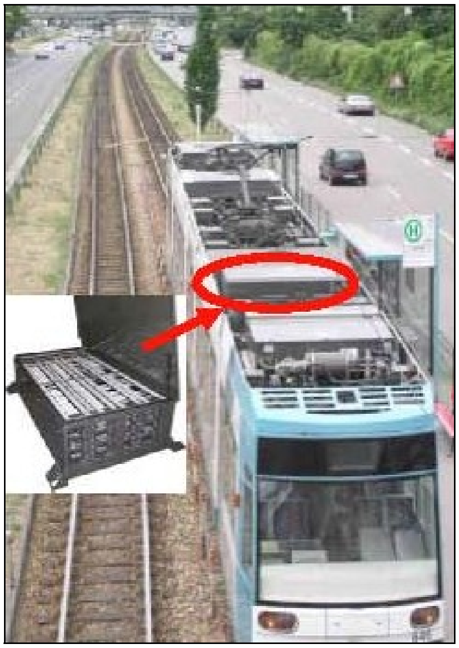

Fig. 22 - Bombardier Mannheim LRV with Ultracapacitor Bank

Ultra-capacitors are also used by the Spanish carbuilder, CAF, to move trams between stations without the need for an overhead wire. Similar to the Bombardier system discussed above, the ultra-capacitors are contained in a unitized compartment, the ACR, and mounted on the roof of the vehicle. The Urbos III streetcar with the ACR option is in service in Seville, Spain. The application permits the Urbos III to run without wayside power between stops and recharges the ultra-capacitor energy storage at stations within 30 seconds. Off wire operational range is reported to be 0.75 miles (1.2 km). In Seville the trams operate off-wire over a distance of 0.3 miles (0.5 km) at speeds of 9 mph (15 km/h) with all auxiliary systems including full air conditioning.

Fig. 23 – CAF Urbos 3

Hybrid Battery/Ultra-capacitor

The combination of both batteries and ultra-capacitors into one system combines advantages of the large storage capacities of batteries and the quick charge/discharge time of ultra-capacitors. The result is a system that can absorb all regenerated braking energy, provide quicker accelerations, and travel off-wire for long distances.

Siemens, a major supplier of rail vehicles, has developed the HES system consisting of both NiMH batteries and ultra-capacitors. The modified Combino streetcar has been operating in revenue service in Lisbon, Portugal since 2008. It can travel off-wire for distances up to 1.5 miles (2.4 km) with grades up to 2.8% and speeds of 20 mph (33 km/h) under normal operating conditions. Recharge time at stations has been reported as short as 20 seconds.

Flywheels

Flywheels, a concept of energy storage that has long been studied, has been given a second look with the development of new composites and integrated control electronics. They serve as a mechanical means of storing energy from braking. They are typically housed in a reinforced vacuum chamber installed on the roof of the vehicle, and rotate at speeds of 20,000 rpm and higher. Energy density is better than for ultracapacitors, though less than batteries. It should be possible to use this technology for short distances or for longer distances if there is a means of intermediate recharging from an overhead supply at passenger stations.

The main drawbacks to flywheel storage is the considerably higher capital cost compared to batteries or ultra-capacitors and the complexity of maintenance over the long term.

Alstom demonstrated a prototype of a flywheel system on a Citadis Tram in Rotterdam, Netherlands, in 2005. The demonstration project used the flywheel for recovery and storage of excess regenerative braking energy. Off-wire operation was tested and vehicles were reported to run at a “reasonable” speed with good acceleration. Data on the distance operated was not available.

CAF also tested a flywheel system in tandem with the original Urbos 2 testing on ultra-capacitors. After testing of both systems on the Seville line, CAF decided to pursue ultra-capacitors instead.

On-Board Power Source Technologies

Several technologies are being investigated that eliminate the need for an external power source altogether. They are typically combined with some type of on-board energy storage technology to power the rail vehicle. These include engine-generator packages (’gen sets’) and fuel cells.

Fuel/Electric Hybrids

This technology employs an engine-generator to produce electricity that is used to power electric motors, eliminating the need for overhead wire. The engine may be fueled by diesel, gasoline, compressed natural gas, or some other combustive product that is stored on the vehicle. This solution is well-known and in widespread use for vehicles such as diesel-electric locomotives. In a hybrid application, the generated power is used in areas without an overhead catenary system and traditional pantographs are used where an overhead wire is present.

An example is the Kassel ‘tram/train’ shown in Figure 24 where the tram operates solely by diesel engine in non-electrified suburban territory and solely by overhead wire within the urban area. There are two diesel-generator sets mounted on the roof of the vehicle. These Alstom Citadis vehicles are 130 feet (40 m) long and 8.7 feet (2.65 m) wide and require 82 foot (25 m) radius curves, which are difficult to fit on urban streets.

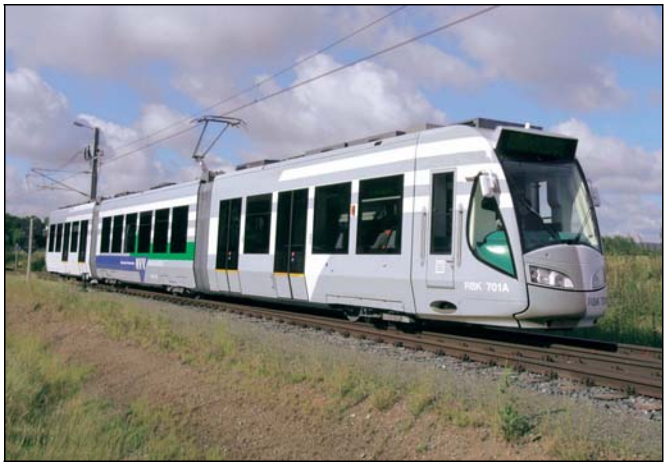

Fig. 24 - Alstom Regio Citadis in Kassel

Another example is the Siemens Combino Dualis used in Nordhausen, Germany. The Nordhausen cars are a modified version of the Siemens ‘Combino’ streetcar platform, and dubbed the ‘Duo’ for their dual-mode capability, they are about the same length as the District’s Inekon streetcars and can turn tighter 50 foot (15 m) curves. The Duo’s are equipped with a single 3.9 liter engine and 180kW generator placed in a compartment inside the passenger area of the car. The engine/generator is housed in the compartment between the two sets of doors, and the fuel compartment is located between one set of doors and the articulation unit as shown in Figure 25 below.

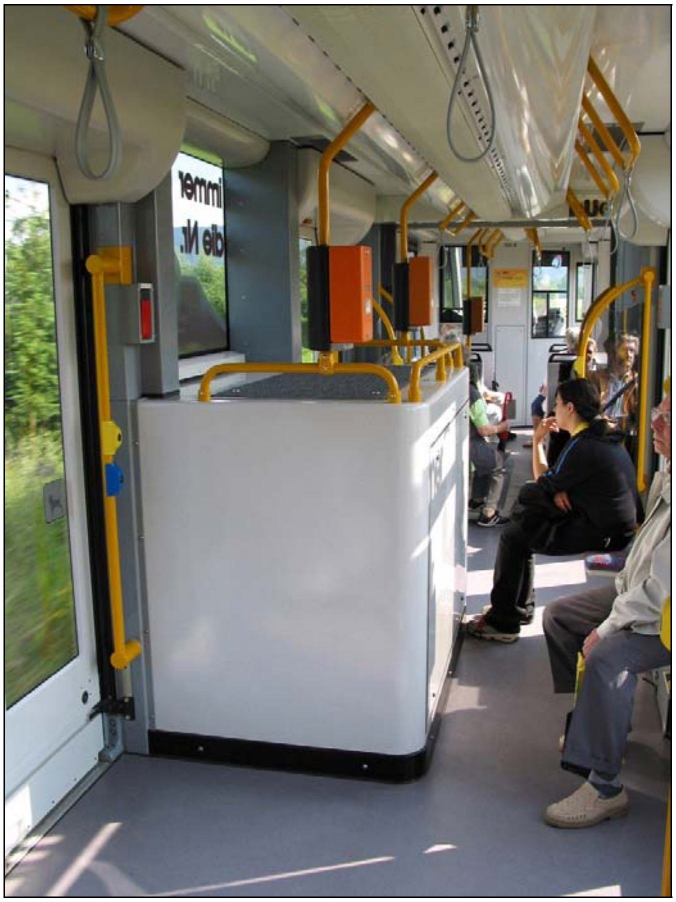

Fig. 25 - Engine/Generator (Siemens)

Fuel Cells

The development of fuel cells for use in the transit industry is still in the very preliminary stages with no known applications to streetcars. There are several demonstration projects with electric buses, and 10 prototypes are currently in revenue service at AC Transit in Oakland, CA. The prototypes are using proton exchange membrane (PEM) cells powered by hydrogen or methanol, with hydrogen getting the most interest. The buses use the fuel cells to drive electric motors as well as to charge batteries which then can assist the electric drives. The fuel cells essentially replace the engine-generators described in the preceding section of this report.

The FTA has funded research in fuel cell-powered buses since the late 1990s at Georgetown University and in 2007 began the National Fuel Cell Bus Program to push further development. Concurrent with this effort, the California Air Resource Board has instituted a similar development program. In the diagram shown in Figure 26, the fuel cell generates electricity which is routed through propulsion control equipment to operate electric motors connected to the bus axle. The electricity is also used to charge batteries which can supplement vehicle movement.

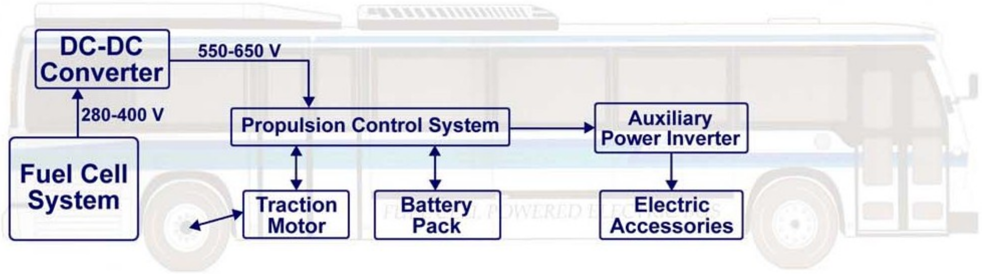

Fig. 26 - Functional Diagram of a Fuel Cell Bus

IMPLEMENTATION ISSUES

Modern alternatives for off-wire operation of rail vehicles are feasible, and vehicles using the many of these technologies have been in revenue service since 2003, as described in the sections above. However, the modern alternatives are still in their infancy with limited applications, to date. Each method brings unique issues to the construction and operation of the system. This section presents a basic listing of the anticipated issues for each technology.

Wayside Technologies

The sub-surface contact rail previously used in the District is no longer considered viable for the following reasons:

- The construction costs and utility relocations, and automotive traffic disruptions required for the installation of the underground contact rail (Figure 5) would be onerous.
- Operation of the systems requires underground chambers staffed by two maintainers at each entry and exit to the wireless area to install or remove the high voltage collector shoe.

- The in-street slot would leave high voltage rail exposed and susceptible to damage from items that may be dropped or intentionally inserted into the slot.
- Weather and drainage impacts on the alignment have been previously documented as shown in Figure 8.

The surface-mounted contact rails have been in revenue service in France on segments with reserved right-of-way for streetcar operation. The systems will also require in-ground distribution and switching networks that will substantially increase construction costs and equipment costs. Some specific issues that will need to be addressed prior to implementation of this type of system in the District are:

- The resiliency of the copper bars to repeated impacts from automobile and truck traffic. Mechanical damage will result in the need for accelerated replacement of the conductor rail.
- The ability to maintain a clean surface on the rail for continuous current transfer. Operation with intermittent contact due to dirt or rubber tire residue will result in pitting on the rail and shoe precipitating the need for accelerated replacement.
- The effects of corrosive chemicals such as road salt on the exposed surfaces of the conductor rails.
- Inclement winter weather where ice or snow can prevent contact with the rail surface will need to be addressed.
- The pre-formed rail assemblies will be considered proprietary or patentable and available from a sole supplier.
- The supplier of the wayside system may dictate the vehicle supplier if the technology is considered proprietary or patentable and is subject to licensing requirements.
- The ability of the pre-formed rail assemblies to be shaped around tight curves or to form crossovers with the grounded running rail for multiple line operation.

- The ability to maintain contact on tight vertical curves such as underpasses is unknown.

- Installation and protection of in-street high voltage contactor boxes at frequent intervals.

- Theft of the exposed copper conductor rails.

The non-contact surface rail system transferring power by induction eliminates several issues seen with the contact surface rails, primarily by replacing the copper conductor with an insulator. The following specific issues for the non-contact system have been identified:

- The systems are very new and the experience with them is limited to controlled demonstration lines on dedicated right-of-way only.

- The resiliency of the insulated covers to repeated impacts from automobile and truck traffic needs to be evaluated. Mechanical damage will result in the need for accelerated replacement of the conductor rail.

- The transference of energy from the wayside to the vehicle depends on maintaining a small gap between the vehicle's collector and the supply rail which may restrict the vertical curve capabilities in areas such as underpasses.

- The pre-formed rail assemblies will be considered proprietary or patentable and available from a sole supplier.

- Installation and protection of in-street high voltage contactor boxes at frequent intervals is required.

On Board Energy Storage Technologies

On-board energy storage is a service proven technology dating back to the early 1900's. The main reason for the prevalence of overhead wire distribution systems has been the much lower cost and reduced operating weight of the vehicles. However, recent advances in battery and ultra-capacitor are decreasing these advantages.

One of the main issues with deployment of these technologies has been cost with the historical price for battery storage at $1000/kWh. Recent advances, driven by the electric automobile market, have resulted in decreasing costs and increasing service life. Reports on the declining costs indicate that the $650/kWh price in 2010 will decrease to $250/kWh by 2020. Nissan is currently claiming the cost of the lithium battery pack in the Leaf electric model is $375/kWh.

Another important issue is the weight of the energy storage devices and the impact on the vehicle structure. Historically, streetcars have used Lead-acid or Nickel Cadmium batteries for on-board storage of back-up control power. These batteries typically store only 40 Watt hours per kilogram of weight. The development of NiMH batteries increased the available energy to about 95 Wh per kilogram. Newer LIBs are reaching up to 130 Wh per kilogram. These densities are permitting the storage of over four times the energy for the same weight. (Ultra-capacitors are primarily used for quick discharge/recharge times and have energy densities of only 5 Wh per kilogram.)

All on-board energy storage technologies have limitations with the amount of energy that can be stored on the vehicle versus the amount of energy required to operate across a wireless area. Operation in mixed traffic lanes is particularly difficult to estimate as unpredictable, but normal, events such as an unusually high traffic volume, traffic accident or diplomatic motorcade can extend the time off wire and exhaust the stored energy, before it returns to powered track, thereby stranding the vehicle. When addressing the reserve capacity for contingencies, and whether to make the system redundant to avoid a single point failure resulting in a stranded a vehicle, it is possible to have more reserve capacity than actual capacity required for operation. The lower capacity of ultra-capacitors may also impact operation outside of a reserved right-of-way due to shorter discharge times and less tolerance to traffic delays. Would all streetcars be provided with the capacity required for the greatest off-wire demand or would specific vehicles be restricted to specific lines?

The requirements for recharging of the onboard systems also need to be considered with the intended line operations. Batteries will sustain longer operation off wire, but will subsequently require a longer time under wire for re-charging. For instance, a battery installation providing a 5 mile (8.3 km) range of off-wire operation may need to be under wire for 30 minutes to fully recharge. Ultra-capacitors, which may only attain 0.6 miles (1 km) off wire, are capable of being recharged in as little as 30 seconds, but in this scenario, each passenger station would require a high-reliability high voltage recharge station which will impact the construction budget.

On Board Energy Generation Technologies

Fuel cells are a nascent technology as it relates to streetcar development and is not ready for a revenue service deployment at this time. The use of a diesel-generator to provide power off wire is a well-proven concept. The issue with a diesel power generation is its incorporation into a small streetcar. Some of the issues to be anticipated are:

- The installation and maintenance of the diesel-generator set and fuel tank in the streetcar's passenger compartment as was done in Nordhausen is problematic as shown in Figure 25.
- Installing the diesel-generator and fuel tank set on the roof will require a longer streetcar such as the 130 ft (40 m) streetcar used in Kassel. The roof structure would need to be strengthened in a typical streetcar to support the weight.
- Fueling services for the vehicles at the maintenance facility similar to a bus fueling station will be required.
- The noise and exhaust run counter to the "green" image being promoted.

OPERATIONAL ISSUES

Streetcars are normally operated as single units. Therefore, redundancy of the on-board systems becomes an important consideration. The goal is to have no single failure which renders the streetcar unable to move, thereby requiring towing to remove the car from the line and restoring revenue service. For example, streetcars in Bordeaux have on-board batteries to move the car if the APS system fails, and Bombardier's vehicles will have on-board ultra-capacitors to accommodate failures of the IPT system. The CAF streetcars using ultra-capacitors would need to be capable of traveling to two passenger stations in the event one station's charging system is not functional.

With the on-board energy storage technology, redundancy can be achieved by installing two housings for the batteries or ultra-capacitors. One unit could be associated with each end of the vehicle and be capable of powering the vehicle across the off-wire section on its own. Similarly, accommodating the redundancy requirement with the fuel/electric hybrid would require the installation of two small engines. Each engine would still need the ability to move the streetcar across the off-wire section on its own, though at a degraded level of performance.

The issue of how to move a vehicle with an exhausted power supply should be considered prior to utilizing the on-board storage technologies. The stranding of one vehicle on a streetcar line can shut down the entire alignment as there will be no method for passing a stranded vehicle and blocking a traffic lane in rush hour may result in bad publicity if it occurs with any frequency. The estimation of transit times to ensure a successful crossing while operating without a reserved right-of-way will be difficult.

PROCUREMENT ISSUES

The procurement of a small order of streetcars can be a challenge. Some suppliers, particularly if they have a backlog of booked work, may not be interested in contracting for small quantities of vehicles as it is very difficult to distribute the engineering and other one-time costs among the small order and keep the price affordable, and especially so if they incorporate new technologies and deviate from the suppliers' standard off-the-shelf vehicle platforms. From this perspective, the District must consider the modifications that need to be made to a supplier's existing streetcar. Alternatively, the District may wish to consider a larger order of streetcars for multiple lines to amortize the engineering and development costs.

The carbuilder's experience and staffing will be very important to a successful procurement. The District does not have a large or experienced streetcar maintenance staff to assist with the start-up problems experienced with new systems. It should be noted that Bordeaux's first installation of the Alstom APS required two years of operation to achieve acceptable reliability levels.

An alternative to the traditional method of procuring vehicles to fit the wayside being installed is the "turn-key" approach. In this approach both the vehicle and wayside are procured as one package from a single supplier. The District would accept delivery of the completed operating system. One of the major benefits of this approach is allowing the wayside power systems to be competitively bid against the on-board storage or generation systems.

The table below provides a list of suppliers and their experience as related to the supply of streetcars. The supplier list includes those suppliers known to have expressed an interest in providing streetcars in the United States. It is not intended to preclude other potential suppliers who may not be currently known.

Supplier	Streetcars in Service	Wireless Operation Experience	Turnkey Systems Experience
Alstom	Yes	Yes	Yes
AnsaldoBreda	Yes	On Order (2010)	Yes
Bombardier	Yes	Yes	Yes
Brookville Mining	Yes	Switch locomotives & mining trams	No
CAF	Yes	Yes	Yes
Gomaco	Yes	Yes	No
Inekon	Yes	On Order (2011)	No
Kawasaki	Yes	Yes	Yes
Kinki Sharyo	Yes	Yes	Yes
Siemens	Yes	Yes	Yes
Stadler	Yes	No	No
United Streetcar	On Order (2007)	No	No

Figure 27. Suppliers Interested in North American Streetcar Market

EXISTING VEHICLES

The District currently owns three streetcars manufactured by Inekon and commissioned in the Czech Republic in 2007. The vehicles are currently configured to run only under wire with a minimal off-wire capability designed primarily to facilitate emergency movements to clear traffic in the event of a loss of the overhead wire. The vehicles are currently being stored at the WMATA Greenbelt Facility.

In late 2007 Inekon responded to a WMATA request to look at the possibility of operating off-wire for limited distances at specific intersections where the District's view corridors might be crossed. In December of 2007 Inekon submitted a study indicating a NiMH battery set could be installed on the vehicle to provide off-wire distances of up to ½ mile (0.8 km) at speeds up to 10 mph with currently available batteries. The primary limitations were the short length of the vehicles and the weight of the batteries. In the last four years LiB batteries have been advanced to the level that it should be possible to increase the calculated range significantly while remaining within design limitations. Inekon has also recently announced receipt of award for a Seattle Streetcar order incorporating LiB technology designed to run up to 2-1/2 miles off-wire with a very similar carbody.

If a wayside power supply option is selected, the mounting a new power collector to the underframe or truck of the Inekon vehicles may be possible. However, supplier cooperation and installation of a compatible energy storage device would need further investigation.

SUMMARY

For a small-to-medium order of vehicles, the right technology will be highly dependent on supplier interest and the status of the design. A new start-up operation should concentrate on technologies that have an established service record and require minimal refinements for their intended use in the project at hand. The table in Figure 28 offers a subjective comparison of the readiness of these alternatives for application on the wayside or on-board rail vehicles.

Option	Proof of Application	Supplier Interest	Procurement Risk
Alstom APS Surface Contact Rail	Revenue	Moderate	Sole Supplier
AnsaldoBreda TramWave Surface	Demonstration	Moderate	Sole Supplier

Option	Proof of Application	Supplier Interest	Procurement Risk
Contact Rail			
Bombardier PriMove Non-Contact Rail	Demonstration	High	Sole Supplier
Batteries	Revenue	High	Low
Ultra-Capacitors	Revenue	High	Low
Fuel/Electric Hybrids	Revenue	Moderate	Low

Fig. 28 - Readiness of Alternatives for Further Examination

Another primary concern is the cost of constructing and maintaining both the wayside infrastructure and the vehicles themselves. These costs are dependent on the option selected and are summarized in relative terms in Figure 29 below.

Option	Infrastructure Costs	Vehicle Costs	O&M Costs
Alstom APS Surface Contact Rail	Increase	Moderate	High
AnsaldoBreda TramWave Surface Contact Rail	Increase	Moderate	High
Bombardier PriMove Non-Contact Rail	Increase	Moderate	Slight
Batteries	Reduction	Moderate - High	Moderate
Ultracapacitors	Reduction	Moderate - High	Slight
Fuel/Electric Hybrids	Reduction	High	Moderate

Fig. 29 - Relative Anticipated Costs

With the current state of the technology and the small quantity of vehicles envisioned, it is our opinion that the best option would be a procurement approach open to either the wayside in-ground supply or the battery/ultracapacitor storage on-board the vehicle. The most significant differences between the two is that a battery solution has the lower risk due to the maturity of the technology while the wayside solutions can simplify the construction and operation of the entire network by providing an unlimited distance at a higher cost than the overhead distribution system. An open competitive procurement between the technologies should result in the Best Value for the District of Columbia.

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SECTION C

Wireless Streetcar Applications for the District of Columbia Mayor’s Streetcar Finance & Governance Task Force Presentation

March, 2013

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Wireless Streetcar Applications for the District of Columbia

March 27, 2013

The Starting Point

Portland, OR

Power Supply Alternatives

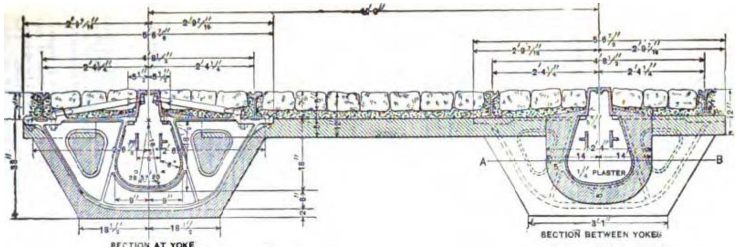
- Ground -Level Power Supply
  - Conduit rail
  - Surface-mounted contact rail
  - Non-contact inductive power
- On-Board Energy Storage
  - Batteries
  - Ultra Capacitors
  - Hybrids

Technologies Reviewed

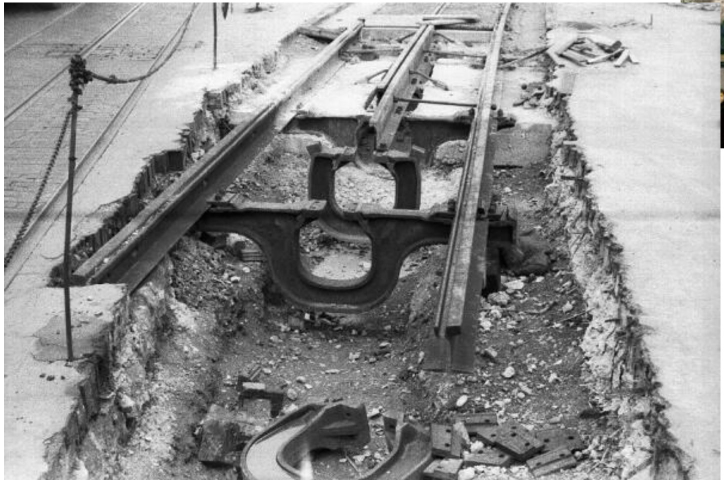
- On-Board Power Generation
  - Fuel Cells
  - Fuel/Electric Hybrids

Ground Level Power Supply

Conduit Rail – *where we were …*



Washington, DC



London

Washington, DC

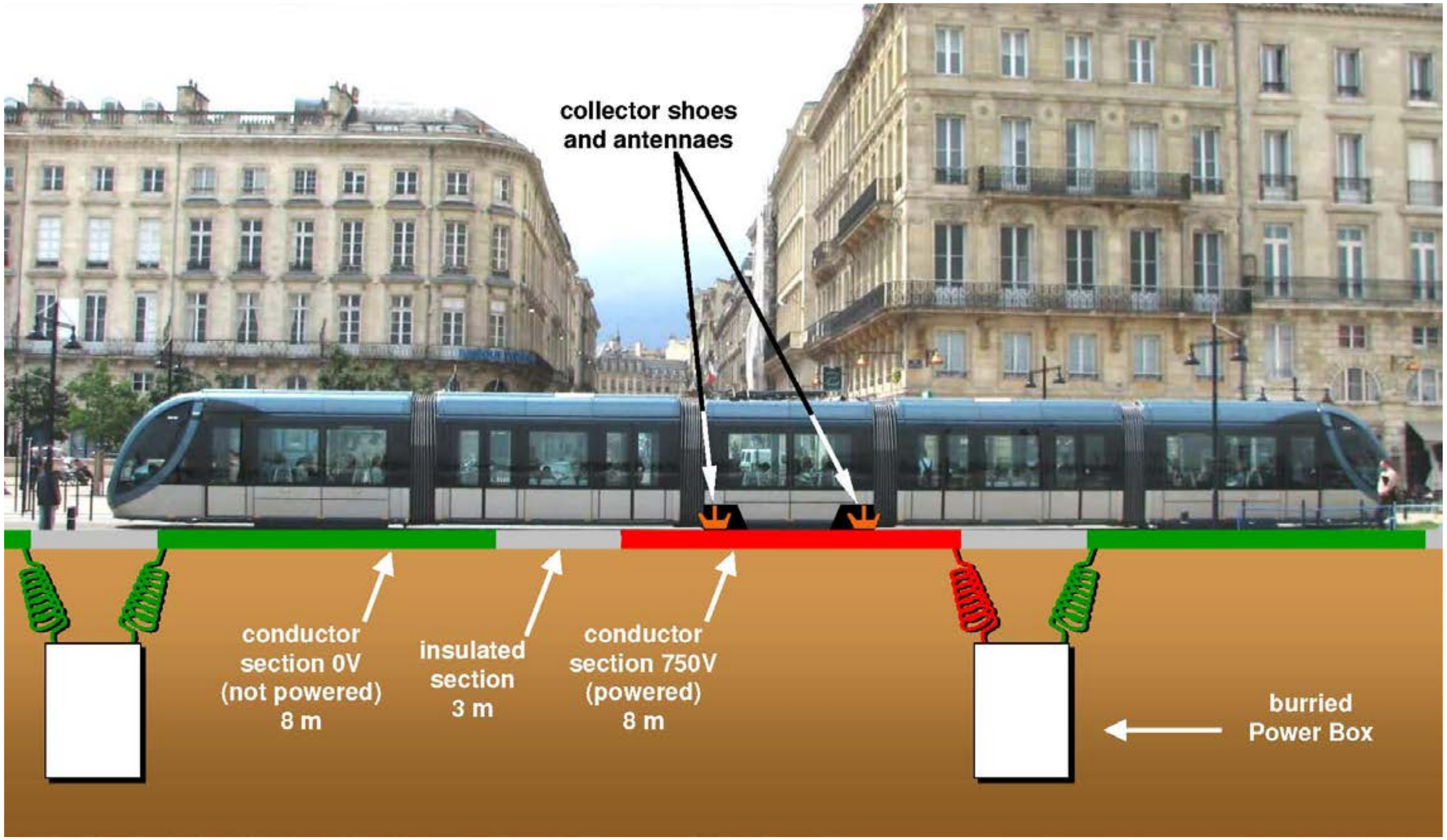
Conduit Rail

Washington, DC

Alstom APS System

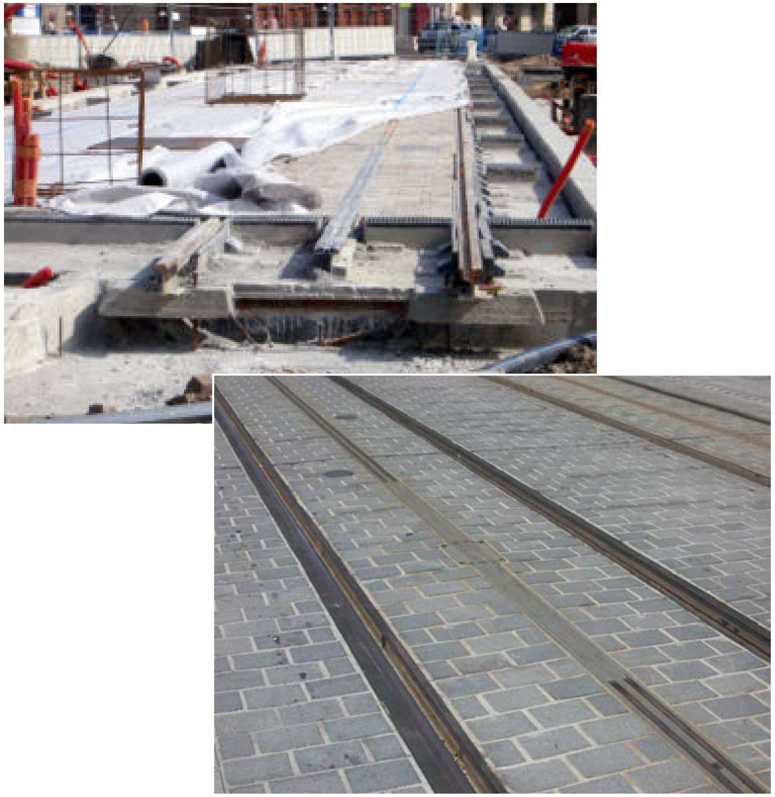
Bordeaux, FR

Alstom APS System


collector shoes and antennaes
conductor section 0V (not powered) 8 m
insulated section 3 m
conductor section 750V (powered) 8 m
burried Power Box

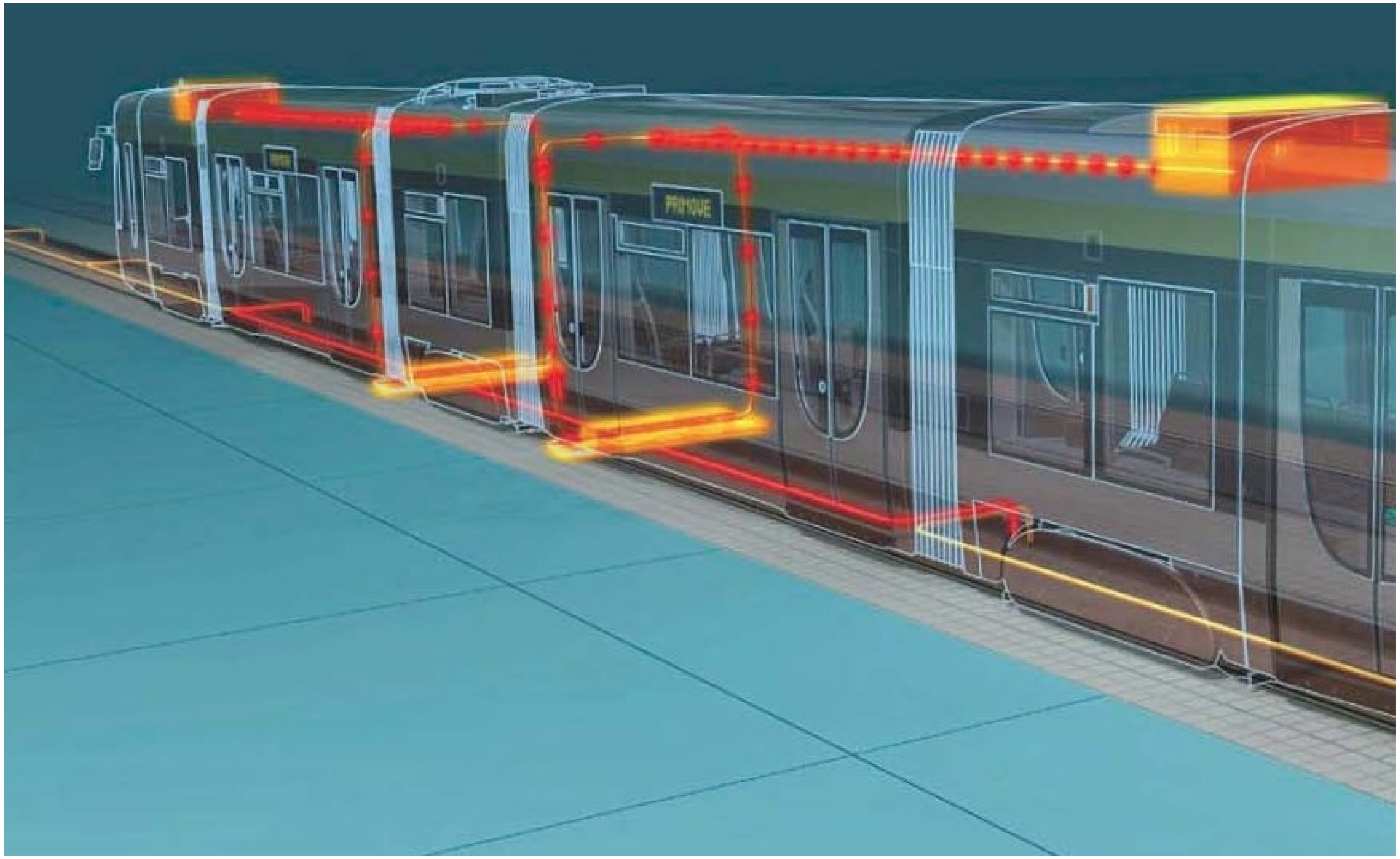
Bordeaux, FR

Alstom APS System

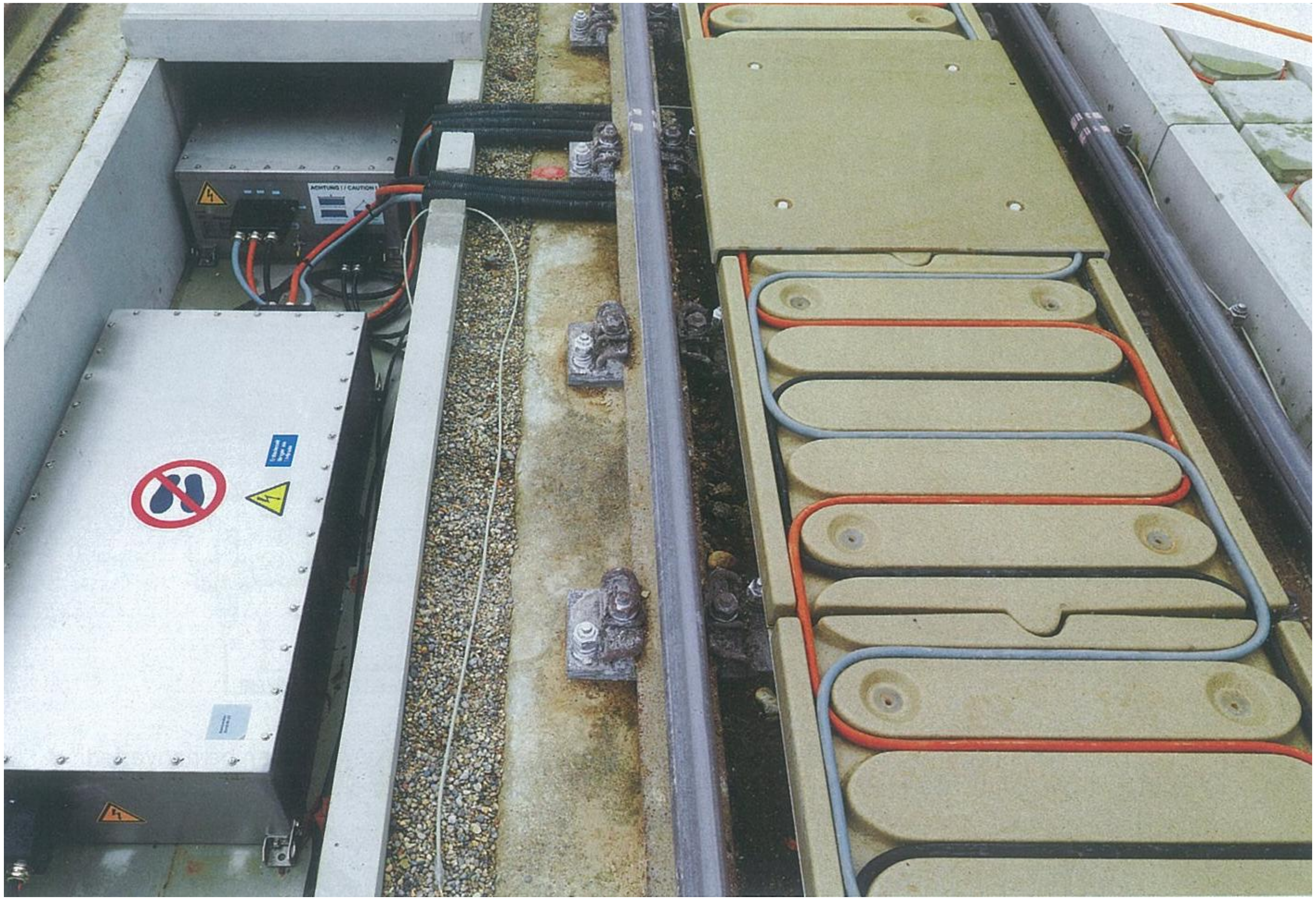


Bordeaux, FR

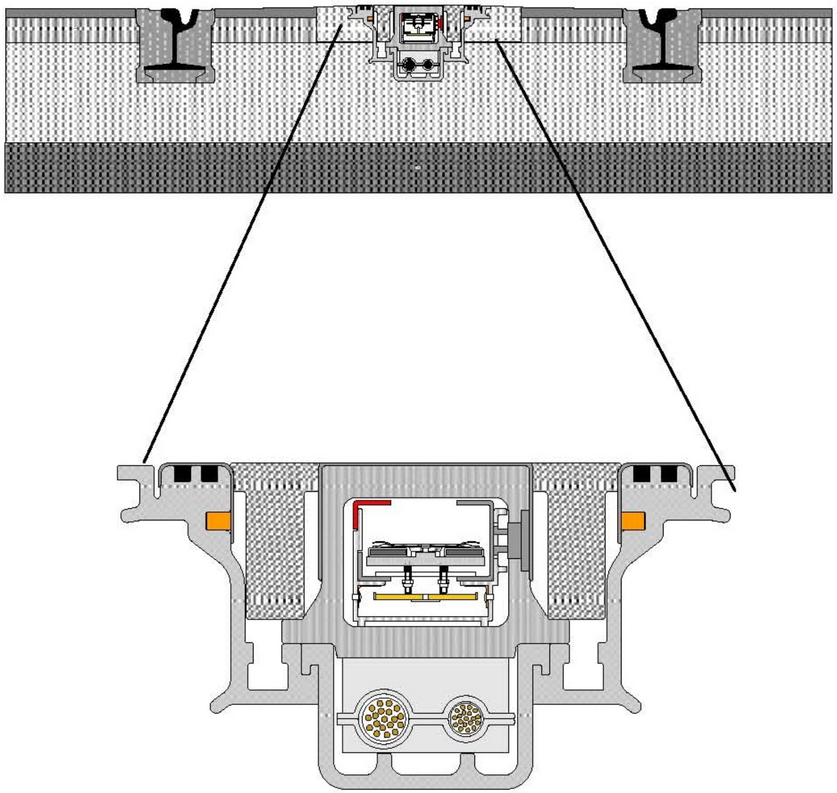
Bombardier Primove System

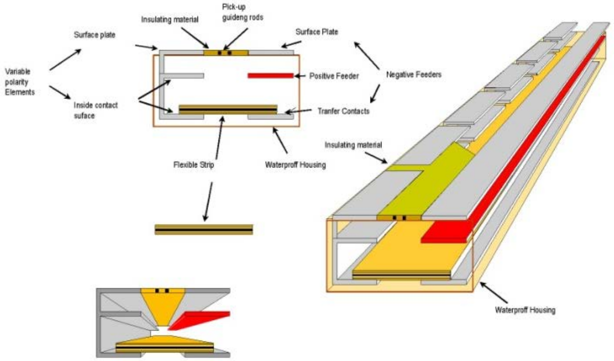


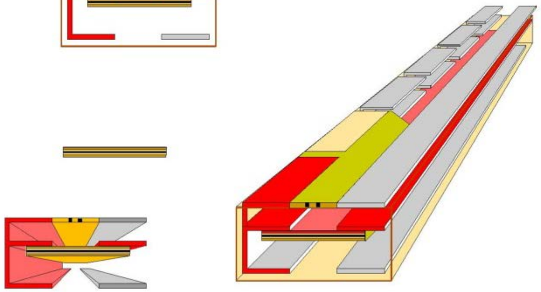
Bombardier Primove System



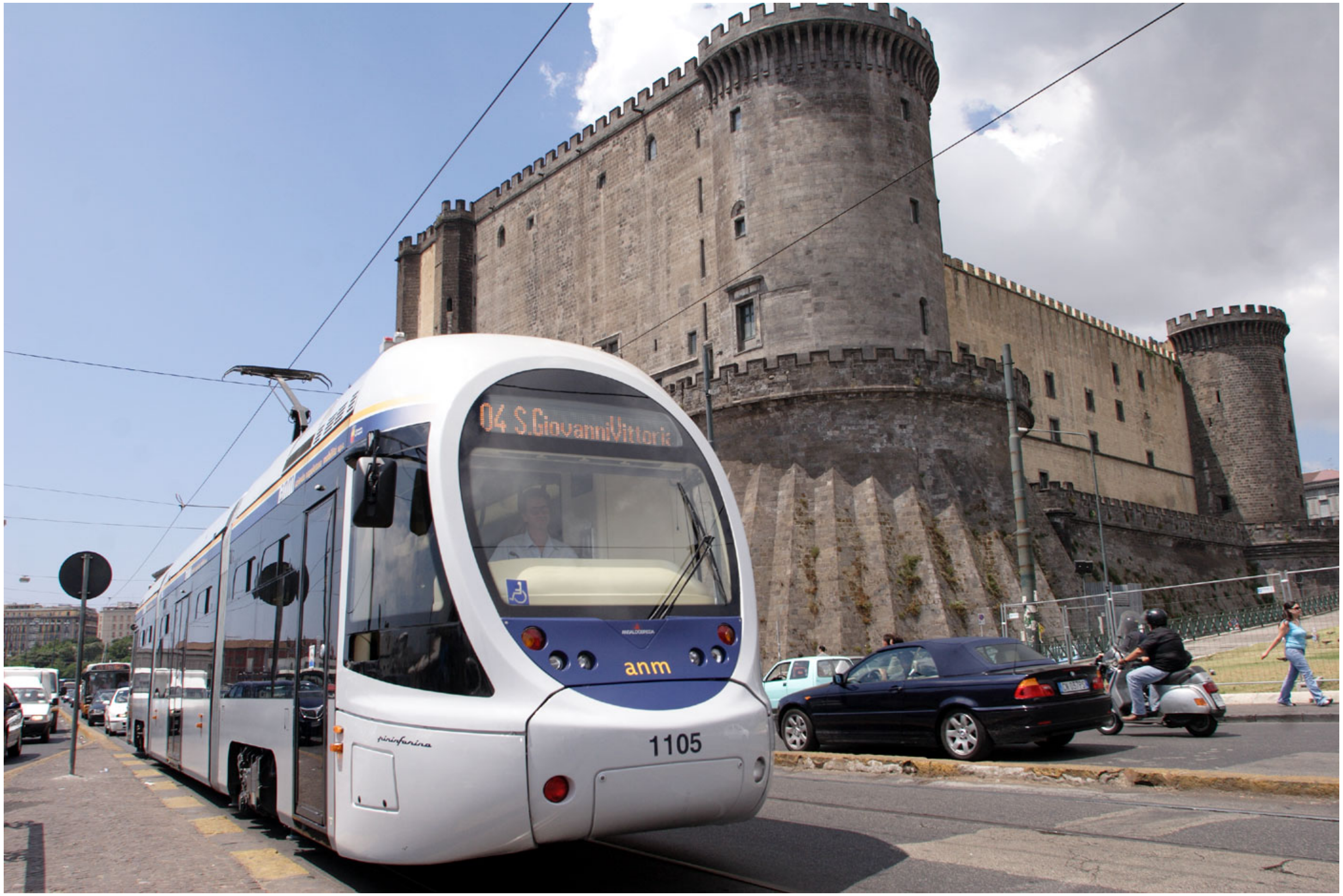
AnsaldoBreda TramWave







AnsaldoBreda TramWave



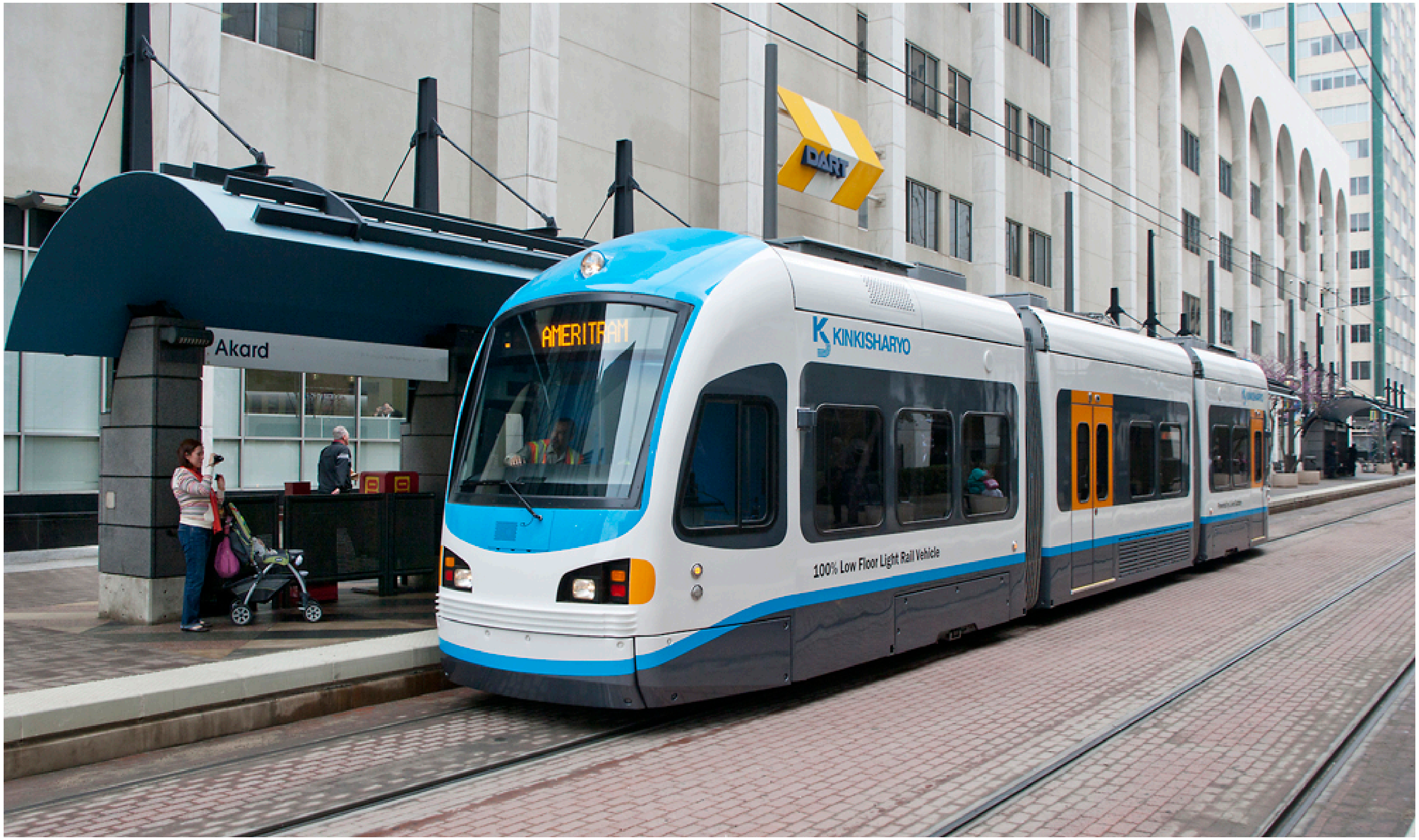
Naples, IT

On-board Energy Storage

Batteries

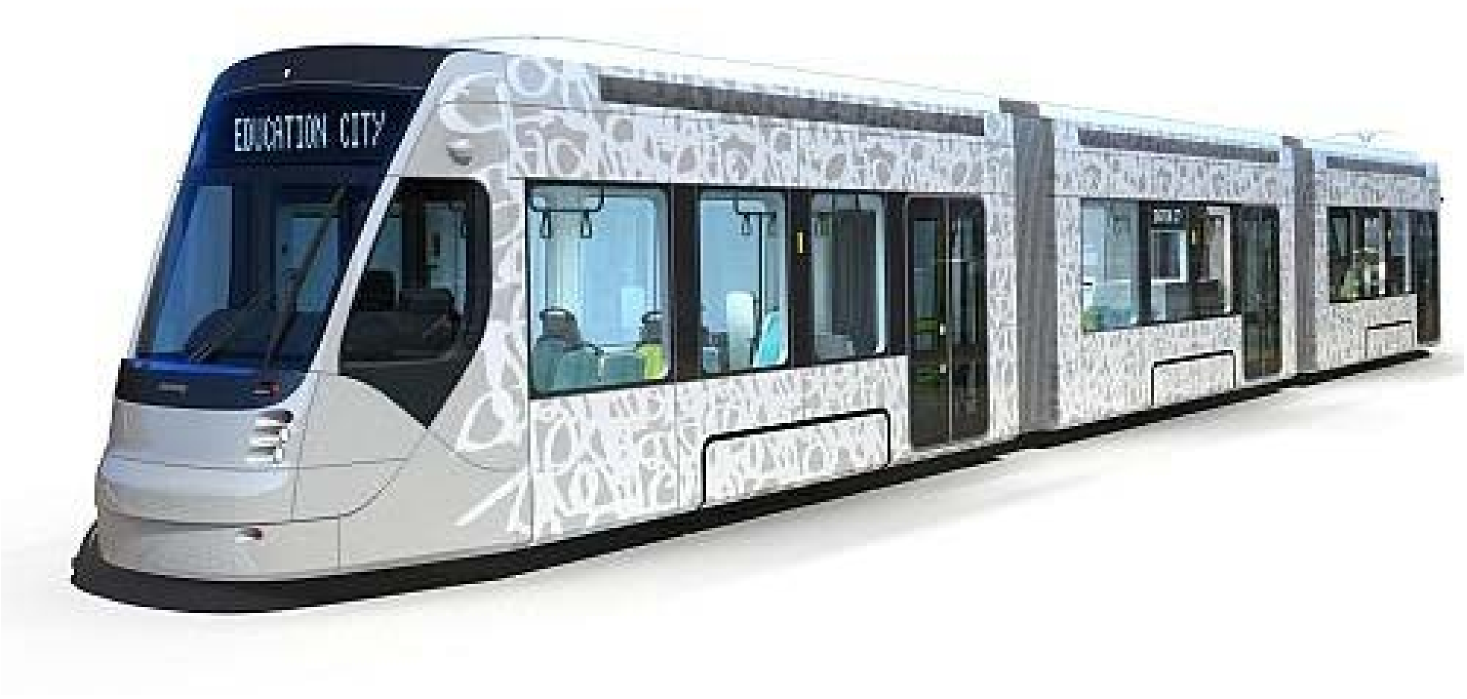
Alstom: Nice, FR

Batteries



Kinkisharyo: Ameritram Prototype

Hybrid: Batteries/Ultra Capacitors

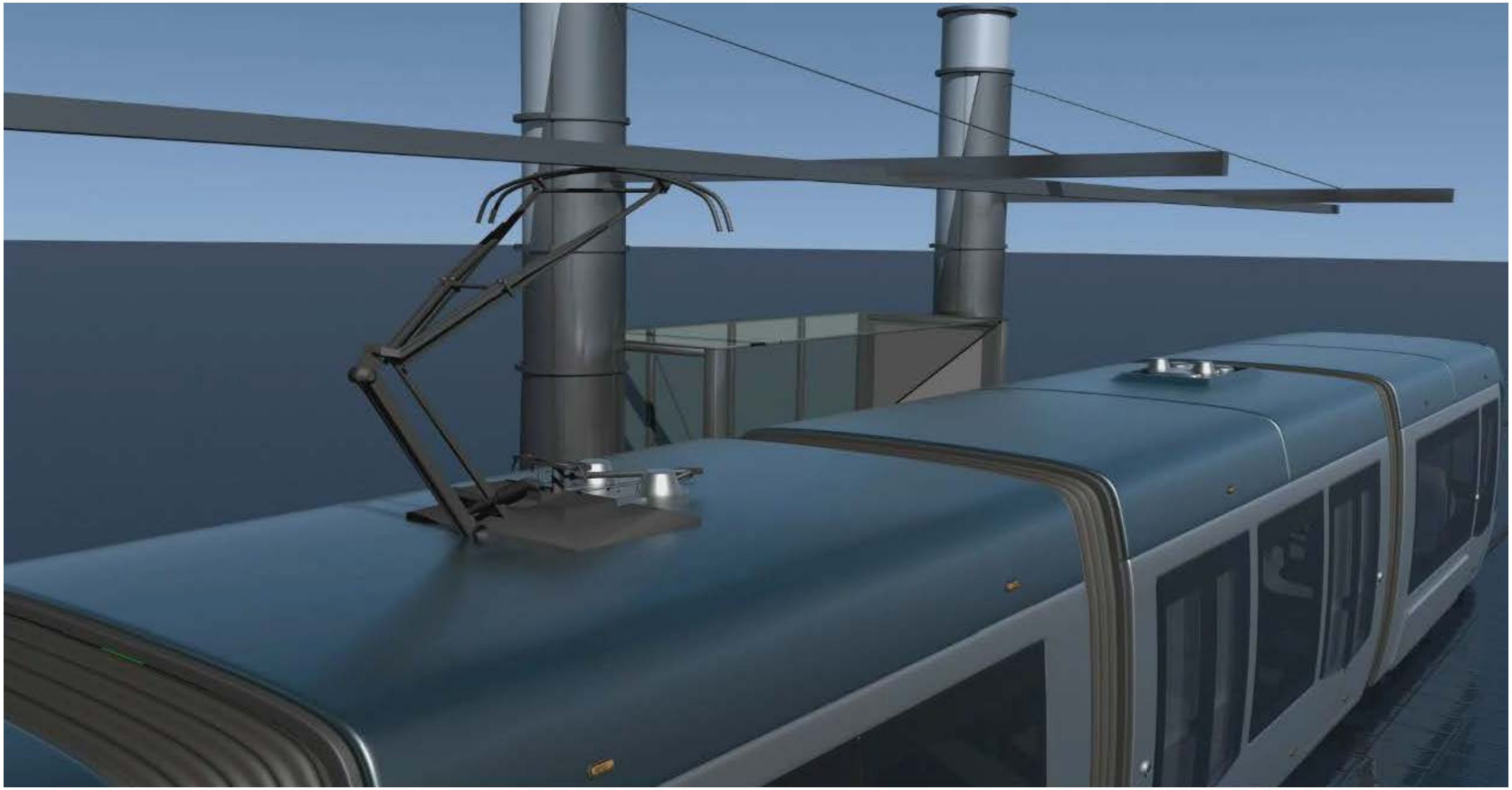


Siemens: Doha, Qatar

Hybrid: Batteries/Ultra Capacitors

CAF: Zaragosa

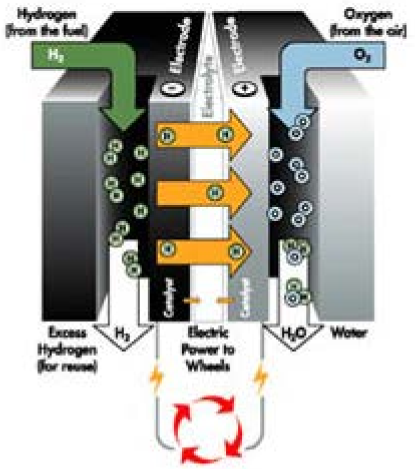
Hybrid: Batteries/Ultra Capacitors



CAF: Charging Concept during Station Stop

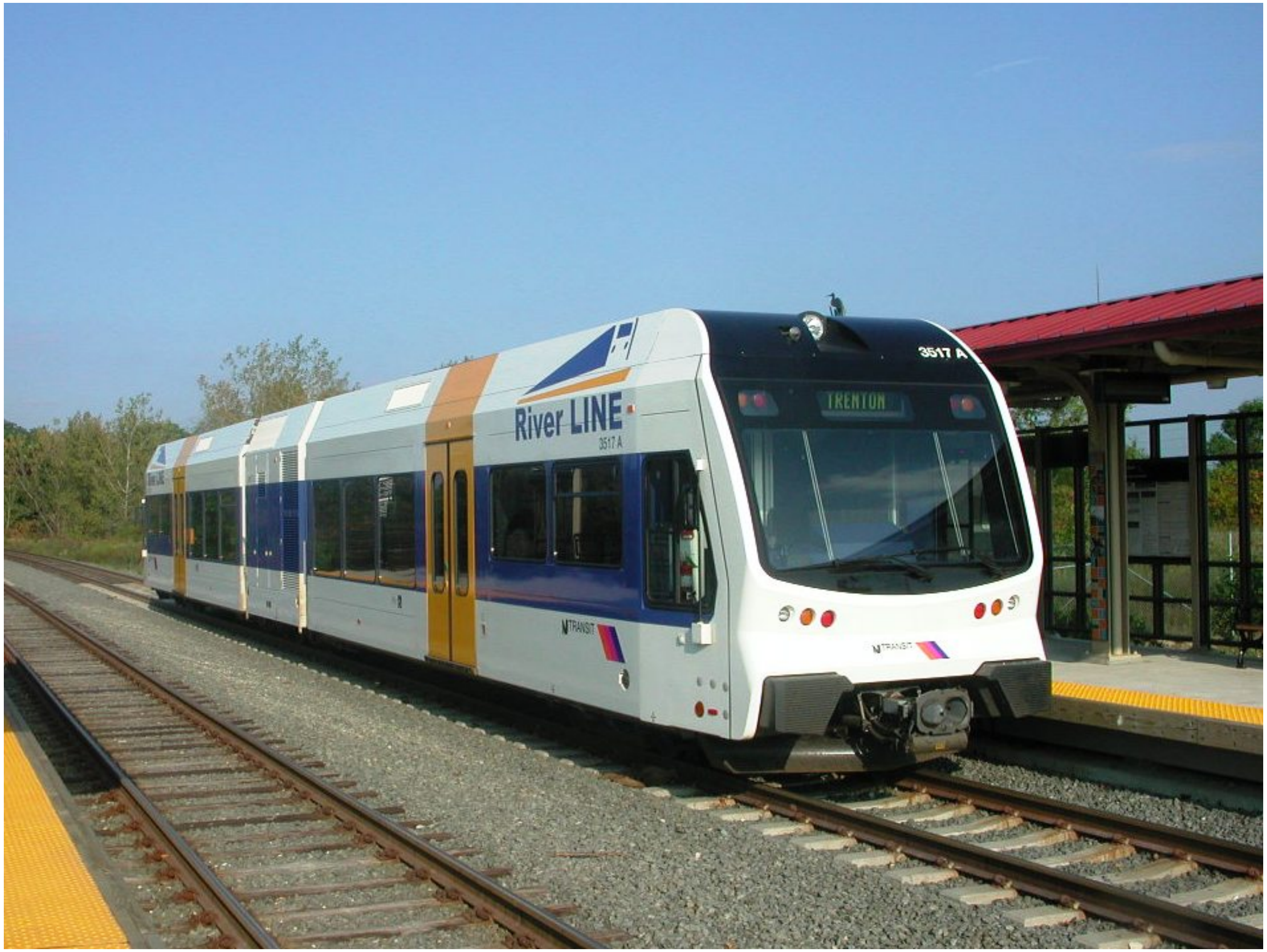
On-board Power Generation

Fuel Cells



AC Transit, Oakland, CA

Fuel/Electric Hybrids



Stadler: NJT River Line, Camden-Trenton, NJ

Fuel/Electric Hybrids

Galveston, TX

Siemens: Nordhausen, GM

Alstom: Kassel, GM

Savannah, GA

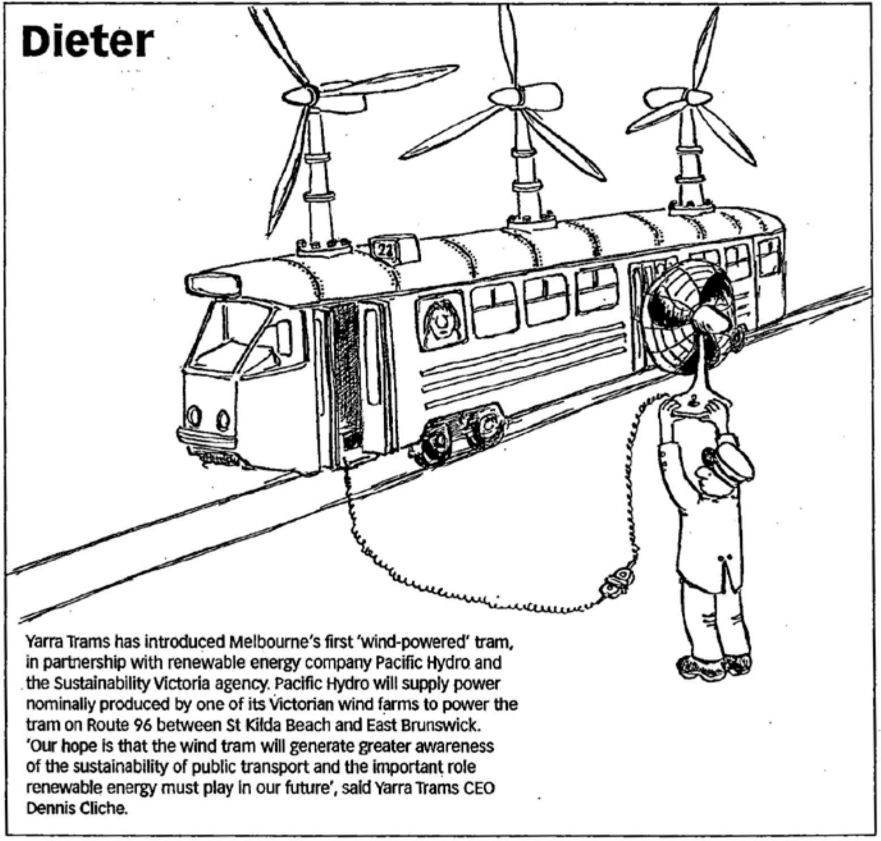
Observations/Considerations

- No silver bullets.
- Only one mature design for ground level power supply – Alstom’s APS; the rest in some form of R&D.
- All such designs proprietary.
- Some not appropriate for Washington DC environment.
- Onboard energy storage applications growing; Seattle and Dallas will be first in US.

Observations/Considerations

- Onboard power generation solutions exist, not ideal for streetcar environment.
- Anticipated high capital cost, whether wayside or on-board; high O&M cost depending on application.
- Most designs originating overseas; may need to consider Buy America implications.
- Technology continuously evolving.

New ideas always popping up



Dieter

Yarra Trams has introduced Melbourne's first 'wind-powered' tram, in partnership with renewable energy company Pacific Hydro and the Sustainability Victoria agency. Pacific Hydro will supply power nominally produced by one of its Victorian wind farms to power the tram on Route 96 between St Kilda Beach and East Brunswick. 'Our hope is that the wind tram will generate greater awareness of the sustainability of public transport and the important role renewable energy must play in our future', said Yarra Trams CEO Dennis Cliche.

Questions/Discussion

dcstreetcar

Questions?

Sandy Castor, 202-671-3499, sandy.castor@dc.gov
Mike Durso, 202-615-9884, michael.durso@dc.gov

http://streetcartaskforce.weebly.com/

Password: taskforce (case sensitive)

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SECTION D

Alternatives Analysis for Premium Transit Service
PROPULSION STUDY
September 2013
(1346 Pages - Digital File on CD)

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UNION STATION to GEORGETOWN
Alternatives Analysis
for Premium Transit Service

PROPULSION STUDY

SEPTEMBER 2013

LIST OF APPENDICES

APPENDIX A – Data Collection Module

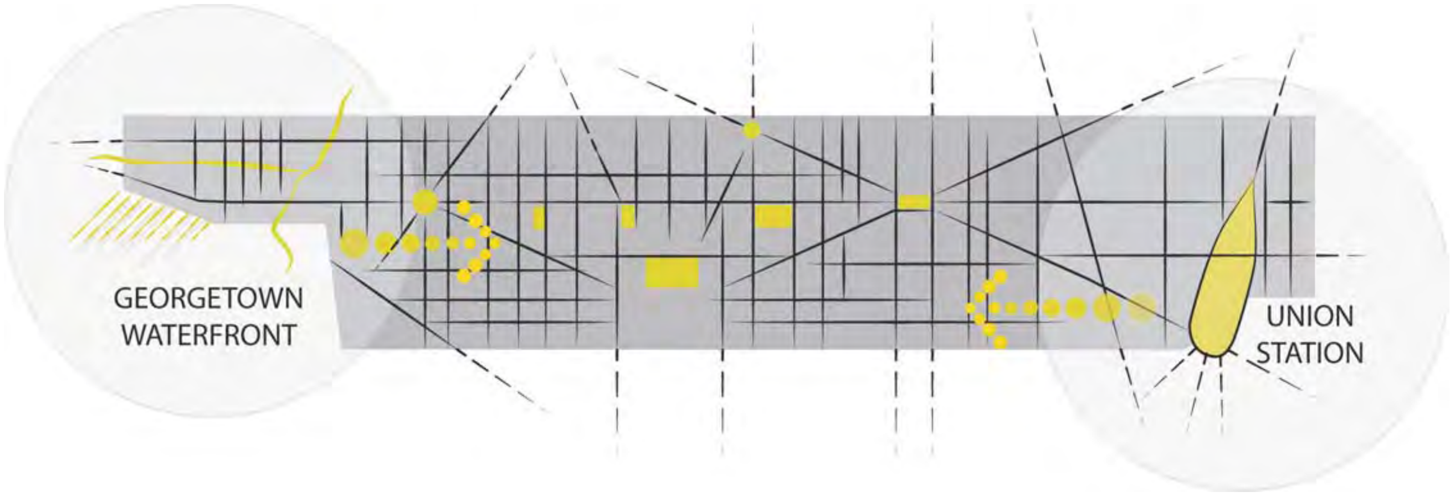
APPENDIX B – Technical / Informative Sessions with Car Builders

District Department of Transportation

Alternatives Analysis for Premium Transit Service
from Union Station to Georgetown

APPENDIX A

Data Collection Module



Data Collection Module Index

Technology Basics

General

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Research Programme

Engineering

Energy storage systems for railway applications

Phase 1

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Author: Rafat Kadhim

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Approved by: David Knights

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Evergreen House
160 Euston Road
London
NW1 2DX
Telephone 020 3142 5534

	Name	Signature	Date
Author	Rafat Kadhim		
Reviewed by	Shamil Velji		
Approved by	David Knights		

Executive Summary

This project assesses the feasibility of using energy storage devices on the railway. It is being carried out in two phases. This report presents a review of existing propulsion and traction hybrid systems and energy storage devices used in both the railways and in the automotive industry.

The report concludes the following:

The issue with super capacitors is cost. The useful lifetime of super capacitors is almost the same as that of traction equipment. Super capacitors have high specific power density but poor specific energy density compared with batteries. Super capacitors installed on a train can be used for storing braking energy and powering the train for distances of up to 500 metres in „discontinuous" electrification schemes. This would enable simplifying the supply design as the train can be self-powered through supply discontinuities in complex areas that contain infrastructure such as bridges, junctions, tunnels, and station throats.

Batteries suffer from a limited life, and cost is also an issue. The useful life of a modern battery is a few years and could be extended to 10 years in railway applications; if the cycle of charging and discharging is maintained at a low level. Batteries can be used for „discrete" electrification schemes to self-power the train for distances of a few kilometres. This application would be suitable to run, for example, dc trams for substantial distances within town.

Modern magnetically loaded composite (MLC) flywheel storage devices have superior performance compared with super capacitors in terms of weight, volume, cost, and lifetime. There are two issues, however, safety and reliability. These are being addressed extensively by the manufacturers of these devices.

Another energy storage option is the diesel hybrid. It is reported that savings of up to 25% can be achieved, provided the energy management system of the train is closely integrated with the duty cycle.

Energy storage devices can also be used in trackside applications, in particular on dc systems, for storing regenerative braking energy and also to smooth out peak load demands.

Batteries can be used to power rail vehicles and other railway-related devices. These applications are entirely dependent on battery size.

To establish theoretical limits for each application, a system-wide theoretical simulation will be necessary. The objective of the second phase of this work is to develop an energy-specific railway model, to address the issues surrounding the use of energy storage devices on the railway.

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Abbreviations

AT	Auto Transformer
BSFC	Brake Specific Fuel Consumption
BSP	Bulk Supply Point
BT	Booster Transformer
CAN	Controller Area Network
CVT	Continuously Variable Transmission
DEMU	Diesel Electric Multiple Unit
DMU	Diesel Multiple Unit
DOD	Depth Of Discharge
DSP	Digital Signal Processing
EDLC	Electrochemical Double Layer Capacitor
EER	Energy Efficient Regulation
EED	Energy Efficient Driving
EET	Energy Efficient Timetable
EMI	Electro Magnetic Interference
EMC	Electro Magnetic Compatibility
EMU	Electric Multiple Unit
ESR	Equivalent Series Resister
EV	Electric Vehicle (battery powered)
F1	Formula 1
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IGBT	Insulated-Gate Bipolar Transistor
IPM	Integrated Power Module
KESS	Kinetic Energy Storage System
Li-Ion	Lithium Ion Battery
LRV	Light Rail Vehicles
LUL	London Underground Limited
M/G	Motor Generator set
MLC	Magnetically Loaded Composite
Na-NiCl	Sodium Nickel Chloride Battery
Na-S	Sodium Sulphur Battery
NiCd	Nickel Cadmium Battery
NiMH	Nickel Metal Hydride Battery
NPV	Net Present Value

OHL	Over Head Line
PMM	Permanent Magnet Motor
PWM	Pulse Width Modulation
SOC	State Of Charge
SLI	Starting Lighting Ignition
SVM	Space Vector Modulation
TFM	Thin Film Foil Lead-Acid
UPS	Uninterruptable Power Supply
VCR	Voltage Controlled Rectifier
VRLA	Valve Regulated Lead-Acid
VSI	Voltage Source Inverter
VTE/SIC	Vehicle Track Energy System Interface Committee
Zn-Br2	Zinc Bromide Battery

1 Introduction

In recent years energy storage technologies have advanced considerably and it is recognised that there are many benefits in using them on the railway. Benefits include reduction in energy consumption, smoothing peak load demands, and savings in initial cost of electrification systems. The potential of energy storage applications on the railway may be grouped into the following areas:

- Diesel vehicle (and fuel cell) hybrids.
- Electric vehicles hybrids.
- Electric vehicles using batteries only.
- Trackside applications on dc electrified lines.

However, cost, lifetime, size and weight remain challenging factors for these technologies.

This project has been set up to assess the feasibility of energy storage systems, with the objectives of achieving energy saving, of reducing the capital cost of ac electrification systems, and possibly improving reliability and safety.

The project is part of the RSSB R&D programme and is being done on behalf of the VTE SIC. It is being carried out in-house by RSSB technical experts in rail energy and power supplies.

The project is being carried out in two phases and this report (issue 2) is the deliverable for phase-1 which has been extended from its original specifications for batteries and super capacitors to include flywheels and hydraulic accumulators. It covers the following areas:

- Literature survey of the present technologies of energy storage systems.
- Preliminary assessment of using energy storage systems on the railway.
- Initial investigation to determine the merits of each application.

The project objectives in phase 2 are to:

- Establish theoretical limits for each of the applications and assess its feasibility.
- Establish additional risks arising from the use of these technologies and propose mitigations.
- Inform future rolling stock / infrastructure policy on the use of energy storage systems for railway applications.
- Identify the most appropriate areas for manufacturers to target new energy storage system applications and developments for the railway.
- Inform what new standards are likely to be needed for new technology areas.
- Contribute to a balanced debate on the future carbon footprint of rail.
- Feed into the technical strategy group V/E SIC, in support of future fuel technology applications.

Section 2 of this report presents a review of existing propulsion and traction hybrid systems used in both the railways and the automotive industry. The characteristics of different types of energy storage systems which are suitable for rail applications are presented in section 3 and 4, for electrical and mechanical types respectively. The main railway applications of energy storage systems are presented in section 5. The report also presents trends and requirements in designing modern traction drive systems that are compatible with the energy storage devices.

2 Review of Energy Storage and Hybridisation

2.1 Energy Storage Systems

Energy storage systems are tailored to the type of fuel used and the form of energy stored, for example: mechanical, chemical, thermal, or electrical. Whilst mechanical storage systems, including flywheels, pneumatic (hydraulic) and elastic mediums store energy in its kinetic form, electrical storage systems, such as batteries and super capacitors store energy in its potential form. One measure to characterise a storage system is to determine the energy to weight ratio (Wh/kg, namely E) and energy to volume ratio (Wh/L, that is, energy density). These two parameters are compared for different forms of energy storage systems in Table 1, (Burke 2005) as reported by Ref 125.

Type of Storage	Wh/kg	Wh/L
Compressed air carbon tanks Isothermal 4500 psi	137	48
Hydrogen carbon tanks 5,000 psi	2,000	700
Hydrogen carbon tanks 10,000 psi	1,666	1,165
Lead acid battery	30	70
NiMH battery	70	180
Lithium Ion battery	120	250
Super capacitor	5	6.5
Conventional Flywheel	3	2
Hydraulics	2	2
Gas oil	11,660	8,750

Table 1 2005 Comparison of energy density of various energy storage technologies, Ref. 125 (Burke 2005)

However, in hybrid traction applications a more important factor must be considered, that is the power density of the storage system (W/kg namely P). Whilst energy density translates into the ability to supply power for protracted lengths of time, power density is an indication of the ability to deliver pulse power at higher levels for a short time. The pulse power may last up to 30 seconds in railway applications. The classical relationship between energy density, E, and power density, P, (Ref. 43) (Christian & Carlen 2000) is known as a Ragon plot, in which a collection of data points are plotted with specific energy density E on the Y-axis and specific power density P on the X-axis as shown in Figure 1.

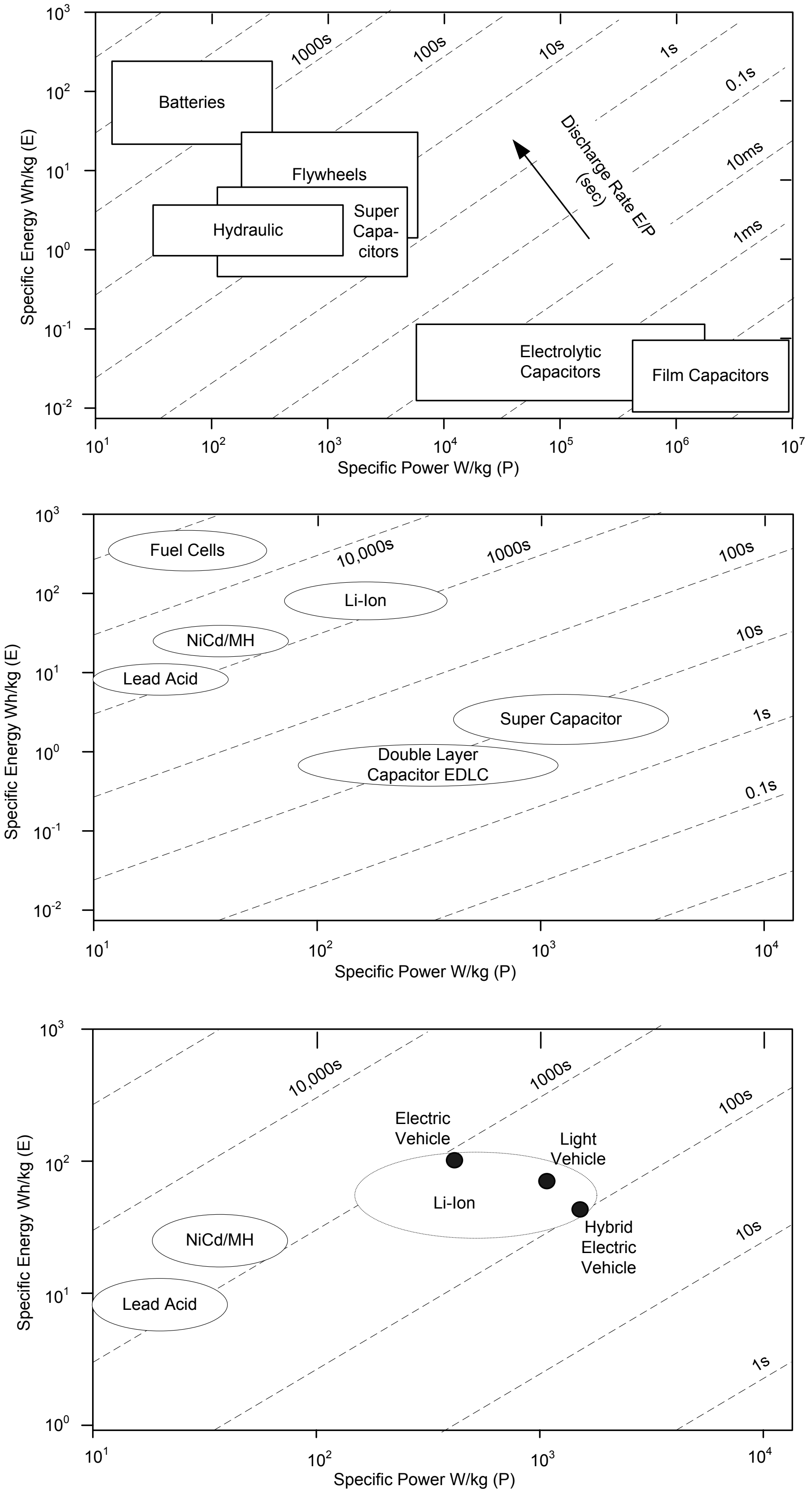


Figure 1 Indicative Ragon plots for different energy storage devices

Figure 1 shows indicative characteristics of different types of storage systems. The data has been compiled from different sources and details are given in Appendix A. It is important to consider the trends rather than the absolute levels as there could be discrepancies between different published data. One reason for this is that many of the published data are commercially orientated marketing materials, which in a number of cases are somewhat biased. Further discrepancies may arise because of the interdependency of P and E; that is, the higher the P the lower the E and vice versa (see section 3.4). Other discrepancies may be explained by the publishing date of the data, as the technology improves the parameters get better, hence the same data published at different times would be different.

Another parameter to consider is the P/E ratio. This is important for traction applications as it indicates the ability of the storage device to deliver peak power compared to its energy storage capacity. The inverse ratio E/P gives the discharging time of the storage system as shown in Figure 1.

Figure 1 also shows that some mechanical systems, such as the flywheel, are as good as, or could be better than, electrical storage systems. Similarly, for specific pneumatic (hydraulic) systems it has been reported that the specific power density is better than the equivalent electric hybrid, excluding the weight of the auxiliary components such as pipes and nuts. (see Ref. 13)(Miller 2003)

2.2 Propulsion Systems and Hybridisation

This section presents a review of the status of hybrids in the automotive industry and focuses on areas where rail applications can be developed.

The approach of the automotive industry, generally, is to undertake a „whole new design" in the implementation of hybrids. For example, the total weight and weight distribution are usually optimised to achieve the best performance (see Figure 2). In comparison the rail industry has attempted, in a few experiments, to introduce hybridisation as an „add on" approach. This approach would clearly compromise performance.

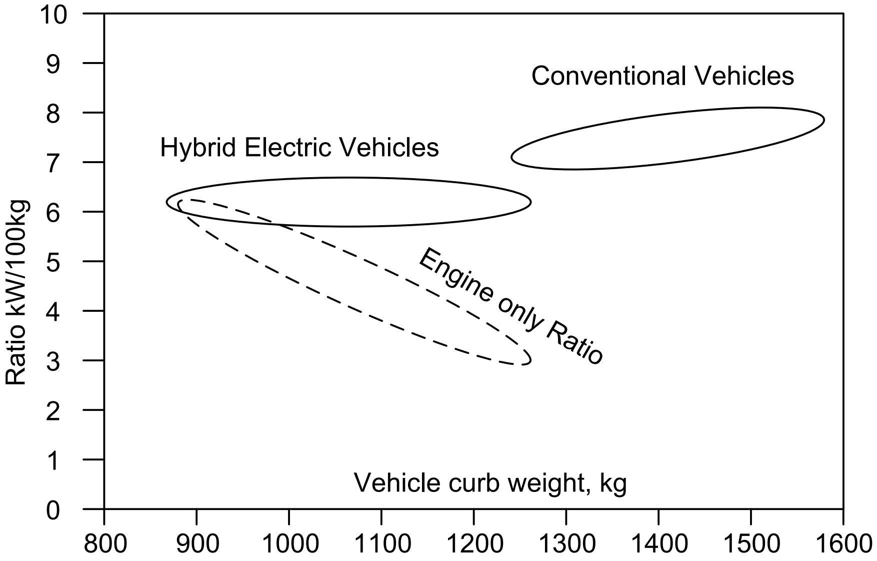


Figure 2 Trend in power to weight ratio in conventional and hybrid automotive vehicles, Ref. 13 (Miller 2003)

For many reasons hybridisation of rail vehicles does not have the same flexibility that is available within the automotive industry. The relatively small numbers of rail vehicles produced, and longer lifecycles, make investments much greater and return on investment periods much longer. This makes it much more difficult to secure funding for such applications.

Existing rail vehicles are driven either by diesel engines or electric power. There are also battery operated vehicles in use for specific applications. Traction load profiles normally exhibit wide differences between peak and average power demand. The ratio between peak and average for shunting locomotives, for example, is greater than six, for semi-fast and suburban trains it is around three, and for intercity and high speed trains less than two. Because of such wide differences between peak and average demands there is realistic scope for hybridisation.

In a hybrid vehicle the power source, a diesel engine for example, could be designed to be smaller than the peak demand when a storage device is used. As such, a ratio between the storage device capacity and the source capacity can be defined to determine the level of hybridisation. The level of hybridisation in rail vehicles may broadly be classified into two categories, mild hybridisation and power assist hybridisation. In mild hybridisation the size of the source is considerably larger than average load demand but smaller than the peak, and in power assist hybridisation the source power matches, or is slightly larger than, average power demand. The level of hybridisation of rail vehicles is depicted in Figure 3 and Table 2.

Power assist hybridisation is an ideal application for a fuel cell design, since the size of the fuel cell is governed by cost. Furthermore, a third hybridisation region may be defined for an externally chargeable battery which runs the vehicle for a limited range, e.g. for a complete journey, but also the vehicle is equipped with a small engine.

The automotive industry have introduced a much wider range for hybridisation levels by subdividing the two ranges further into micro, mini, etc. In addition there is a classification for externally chargeable hybridisation, known as „plug-in", where small engines and much larger batteries are used. In these applications the vehicle is predominantly battery powered being charged up from an external source or, in the case of the railways the traction supply can be used.

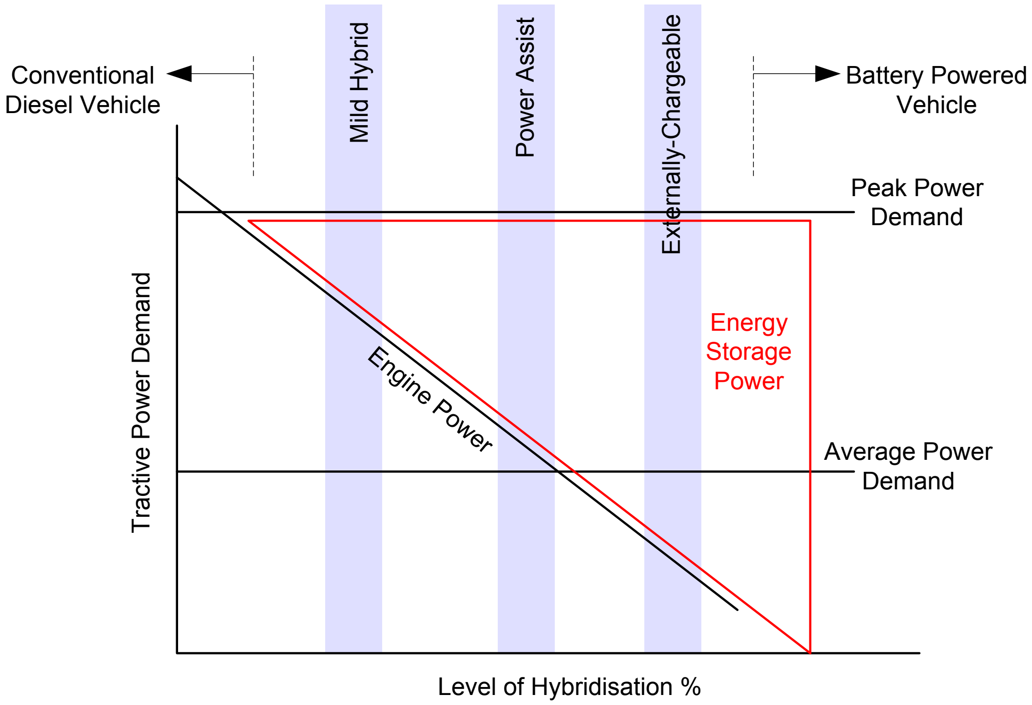
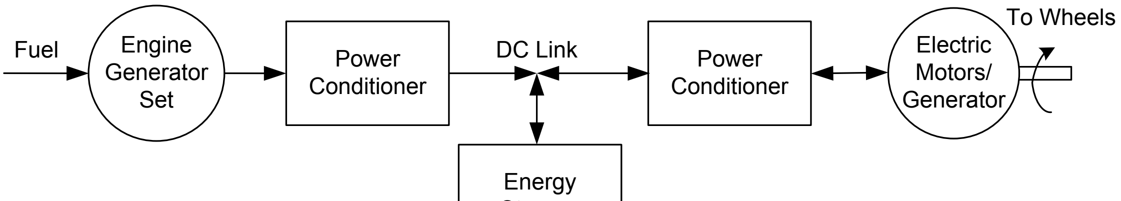


Figure 3 Level of hybridisation in electric hybrid, diesel-hybrid, or fuel cell, rail vehicles

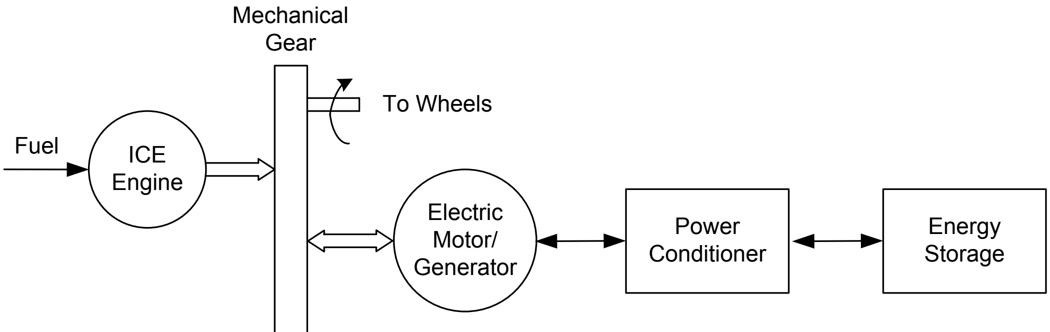
Rail Vehicle	Power Source	Energy Storage	Range
Conventional diesel rail vehicles, e.g. DMUs	No engine downsizing	1-2 %	Fuel tank capacity
Mild hybrid diesel rail vehicles DHMUs	10-20 % engine downsizing	20-30 %	Fuel tank capacity
Power assist diesel rail vehicles DHMUs	20-40 % engine downsizing	30-50 %	Fuel tank capacity
Power assist fuel cell rail vehicles	Fuel cell power slightly larger than average power demand	50-60 %	Set by H2 storage
Externally-chargeable and fuel cell	Fuel cell power much smaller than average power demand	60-80 %	Set by battery size and H2 storage
Hybrid electric rail vehicles, e.g. EMUs	Full power available if OHL or 3rd rail supply exists	10-80 %	Depends on storage capacity
Battery-driven rail vehicles	None, but the battery can be charged from the traction supply	100 %	Set by battery size

Table 2 Diesel, fuel cell or electric hybrid rail vehicles for different applications

Hybridisation designs can commonly be classified into two types, series and parallel as shown in Figure 4. The term series or parallel refers to the way the torque is added from the main source and the energy storage source.



Series Hybrid Arrangement



Parallel Hybrid Arrangement

Figure 4 Series and parallel ICE-battery hybrid arrangements

Most car hybrid designs are based on parallel hybridisation, as the levels of torque required can be added using mechanical devices. In railway hybridisation however, the torque levels are difficult to transmit using mechanical means and therefore series hybridisation is mainly used. Nevertheless it is reported that parallel hybridisation has been used on light rail vehicles such as trams.

There are other types of hybridisation, for example, where series-parallel switching, or shaft-mounted M/G sets, were used, but these have not been covered in this project. The storage system, whether electrical or mechanical, can be used for series or parallel in the same fashion. Figure 5 shows a hydraulic electric hybrid used in a car‟s parallel hybrid system.

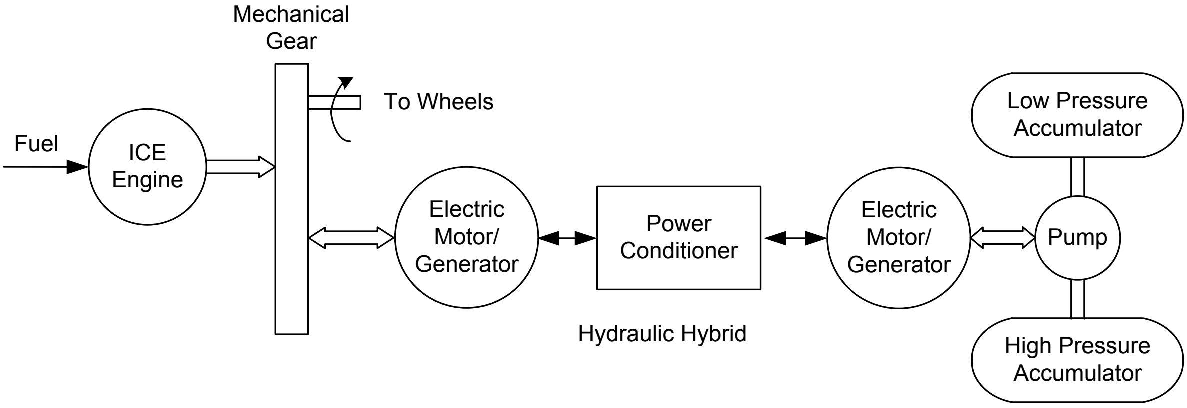


Figure 5 ICE-hydraulic electric hybrid arrangement

In modern rail vehicles, where voltage source inverters (VSI) operate from constant dc link and drive ac motors, hybridisation can be introduced by connecting the energy storage device to the dc link. Generally, this arrangement is considered as a series type of hybridisation and it is universally used for rail vehicle hybridisation. Figure 26 shows a typical power circuit of 25kV pulse converter and ac drive inverter including an energy storage device controlled by a bi-directional dc-dc converter.

The merits of hybridisation of various rail vehicles are summarised in Table 3, and as reported by Ref 30.

	Electric vehicle	Diesel vehicle	Fuel cell vehicle
Propulsion system	Electric traction motors	Traction motors and diesel engine	Electric traction motors
Energy storage system	Battery Super capacitors Flywheel	Battery Super capacitors	Need battery, supercap's or flywheels to enhance power density for starting the vehicle
Energy source and Infrastructure	dc 3rd, 4th rail or overhead and ac OHL	Diesel	Hydrogen (fuel cells) Hydrogen production and transportation infrastructure
Characteristics of a potential hybridization	Zero emissions High energy efficient Not dependent on fossil fuel High initial cost Reduction of the peak power in ac and dc networks	Very low emission Better fuel economy compared to conventional DHMUs and DEMUs Dependent on fossil fuel availability The increase in energy savings and reduction of emission depend on the power level of motor and energy storage unit as well as duty cycle	Zero emission or ultra low emission High energy efficiency Independent on fossil fuel availability High cost Under development
Major issues for hybridization	Appropriate when there are operational constraints (wire-less part of the network) Might be good on dc electrified lines	Multiple energy sources, control, optimisation and management Energy storage unit sizing and management	Fuel cell cost, cycle life, and reliability Hydrogen infrastructure Hydrogen storage

Table 3 Summary of rail vehicles hybridisation, (see Ref 30)

Energy storage devices for railway applications may be classified into two categories, electrical and mechanical. Electrical devices include batteries and super capacitors; mechanical devices include flywheels and hydraulic accumulators. The two types of energy storage are described in sections 3 and 4 respectively.

3 Batteries and Super Capacitors

3.1 Batteries Used in Hybrid Systems

A battery is a collection of electro-chemical cells that convert chemical energy directly to electrical energy via an isothermal process having a fixed supply reactant. The battery consists of anode, cathode and electrolyte in a suitable container. Electrons are transported through the electrolyte generating potential across the cell. The battery has constant energy density for the particular choice of active materials.

In assessing the suitability of battery systems for traction applications it is more important to focus on the terminal characteristics rather than the chemical processes involved. As such only those battery behaviours relevant to railway applications are presented. In the typical operating conditions of a railway system the key parameters of a battery that need to be considered are: operating temperature, rate of charging/discharging and the level of depth of discharge (DOD). These are described briefly in this section and more detail is given in Appendix B.

Generally, the two main parameters influencing the terminal voltage of a battery are the ambient temperature and the rate of discharge of the battery (C). Figure 6 and Figure 7 show the nature of these two parameters. The diagrams shown are not to scale and are intended to show the trends only. The characteristics shown in Figure 6 will shift to the left if the discharge rate increases, and similarly in Figure 7 the characteristics will shift left when the temperature increases.

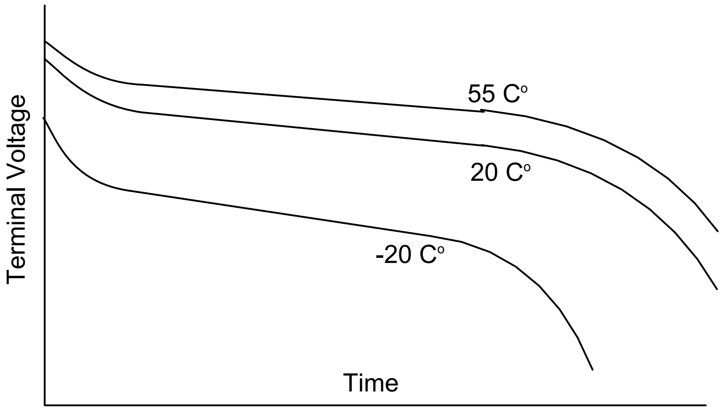


Figure 6 Terminal voltage of a battery at different operating temperatures and constant C rate

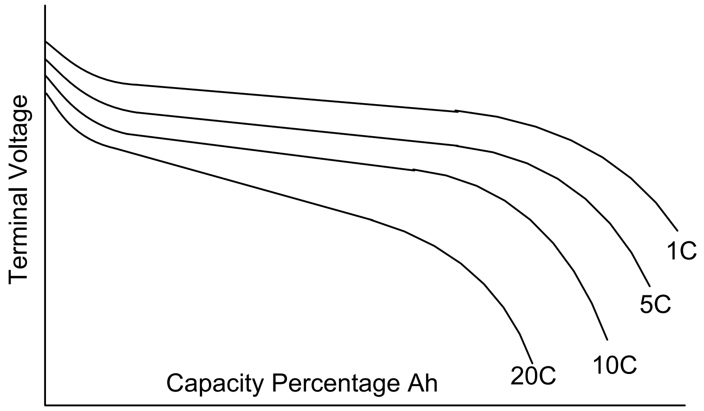


Figure 7 Terminal voltage of a battery at different C discharging rates and constant temperature

The battery capacity is defined by Ah rate and C rate. The C rate for a lead-acid battery, for example, is usually given at C/20 meaning a complete discharge takes 20 hours. As such, a 60 Ah battery would discharge at a constant 3A for 20 hours. This however does not mean the battery would discharge at say 6A for 10 hours, as a higher discharging rate will reduce the capacity, as depicted in Figure 7.

Another important parameter to characterise the battery is the level of depth of discharge (DOD). There are a limited number of deep discharge cycles, above 80% DOD, during the useful life of the battery. This is of utmost importance in railway applications as the load is continuously varying, with a wide difference between the minimum and maximum levels.

As regular deep discharging of the battery dramatically shortens its life, the trend in designing battery hybrid propulsion systems is to oversize the battery, thereby maintaining the state of charge (SOC) above a specified threshold level that minimizes sulphation and lengthens the useful life of the battery. Clearly, the penalty for this is larger weight and size of the battery.

For a system-level investigation, such as the railway model proposed for phase 2, the battery can be modelled using high-level metrics, based on lumped parameters. This approach provides acceptable results compared to the real world, which would also be beneficial in sizing and costing studies. The models used for this purpose are shown in Figure 8.

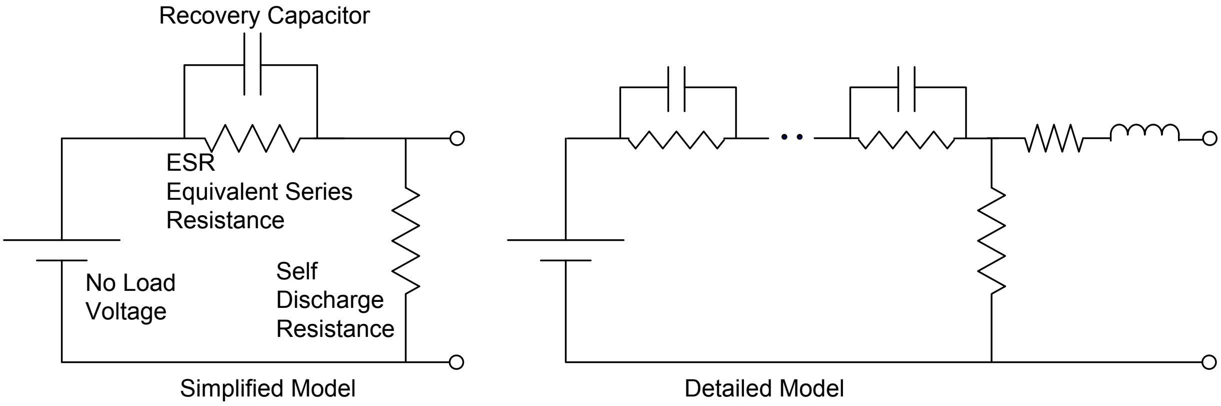


Figure 8 Simplified and detailed equivalent circuit of a battery

Given that the charging and discharging currents always flow in the equivalent series resistance (ESR) it follows that higher efficiency is obtained at lower charging and discharging current rates, and vice versa. As such there is a limit to the maximum efficiency of a round charging/discharging cycle in a railway application as the traction currents are determined by load demands.

The battery parameters shown in Figure 8 are highly non-linear (in fact any electrical component is non-linear and the circuit theory is only an approximation based on linearisation of circuit components). These parameters are dependent on the SOC, temperature, discharging rate, and the remaining useful life of the battery. The non-linearity of the circuit is expected, as the model shown in Figure 8 attempts to represent a chemical process by electrical circuit components. For the purpose of designing the traction equipment of a hybrid vehicle, a much more detailed model will be needed. More refined and complicated models are available but are outside the scope of this report.

Generally, battery systems for hybrid vehicles are optimised for shallow cycling (as low as 10%) and have a higher rate of cycling. Thus, the battery life is extended as deep DOD (greater than 80%) is avoided. For EV, shallow cycling is not possible and as such the battery life cannot be extended by the same rate. For comparison, the sustainable number of deep discharges in a super capacitor is at least 10 times more than that of a battery, and therefore its useful life is considerably longer.

3.1.1 Lead-Acid Batteries

Lead acid batteries are among the oldest known rechargeable electro-chemical batteries. These batteries are used as standard starting-lighting-ignition (SLI) in conventional cars. In the 1970s maintenance-free batteries were developed, using calcium and other additives, to control sulphation and improve the current collectors. Valve-regulated technology was used to develop advanced lead-acid batteries. Known as VRLA lead-acid batteries, these have a longer life than the conventional lead acid battery and are more flexible.

A typical lead-acid battery has a cell potential of 2.1V, specific energy of 35-50 Wh/kg and energy density of 100 Wh/L. Lead-acid batteries are typically characterised at a C/20 discharge rate, where C is the capacity of the battery in Ah. Higher discharge rates incur higher internal losses and lower resultant useful power.

3.1.2 Nickel Metal Hydride Batteries

This battery employs a chemical composition of either lithium-nickel or titanium-nickel alloy, used with potassium-hydroxide electrolyte, to form the NiMH cell. The capacity of NiMH is relatively high but the cell potential is only 1.35V. The specific energy is around 95 Wh/kg and the energy density is around 350 Wh/L.

NiMH does not have high discharge rate capability and suffers from high self-discharge, typically 30% /month at 20 C^o. NiMH batteries are sensitive to overcharge/discharge and have very reduced performance at cold temperature, (see Figure 6). For this reason some systems using NiMH batteries employ a climate control system such as heaters in cold weather. The NiMH cell diminishes rapidly as the discharge rate increases. Charge acceptance is another problem with NiMH batteries. Because the cell voltage variation is very small with increasing SOC, control of NiMH batteries is more difficult than other types of batteries.

NiCd batteries are based on the same principle; exhibiting a relatively high discharge rate, they also suffer from „memory" effect. NiCd batteries, however, cannot be used in hybrid systems as they contain highly hazardous materials.

3.1.3 Lithium-Ion Batteries

A lithium-ion cell contains a lithium-manganese-oxide alloy, as the cathode and the anode are carbon, typically bound within the host lattice to form the lithium-ion cell. Lithium-ion batteries have nearly reciprocal charge-discharge characteristics. The cell voltage is as high as 4.1V when open circuit (3.68V/cell -30% to +17.6% under load). The specific energy is around 125 Wh/kg and the energy density is more than 300 Wh/L. Cycle life at 100% DOD is more than 1,000 and operating temperature range is -20 C^o to +45 C^o. The usable SOC of a lithium-ion battery is nearly four times that of lead-acid batteries. The lithium-ion battery can easily operate from 100% to 10% SOC before recharge. This makes it very suitable for hybrid vehicle applications.

However, lithium-ion batteries, like NiMH, require an accurate charge/discharge management system, which can generally be achieved using microprocessor controllers. Also lithium-ion batteries are larger than NiMH batteries. The lithium-ion battery is sensitive to over-charging or over-discharging with the potential of fire, for which only CO^2 extinguishers can be used.

Recently there have been significant improvements in lithium-ion battery technology. Pool (2008) [Ref. 68] reports a considerable increase in battery life with the use of new materials. It is claimed that at DOD of 85% the battery can withstand 25,000 cycles without degradation in its performance.

Nanotechnologies and nanomaterials continue to improve (see Ref. 154). It is claimed that developing lithium-ion batteries containing specific proprietary nano-titanate material instead of graphite can charge and discharge significantly faster and more often than existing lithium-ion batteries. The nano-titanate material does not expand or shrink when ions enter and leave its particles during charging and discharging, therefore increasing its life over graphite. Existing lithium ion batteries have a useful life of 750 charges, while the new batteries can be charged over 9,000 times while still retaining 85 percent of their charge capacity. The batteries can be charged to 80 percent of their capacity in about one minute. However, nano-titanate batteries are not available commercially. Their characteristics compared with other forms of storage devices are shown in Figure 12 (section 4.2).

Given the state of current battery technologies it is clear that lithium-ion battery use is at the top of the list in hybrid rail vehicles.

3.1.4 Other Types of Batteries

Extensive research and development is being carried out to develop new types of batteries, including research to improve the commercially available batteries such as lithium-ion. Appendix B presents a number of new battery types under development, details of which are outside the scope of this report.

Among these batteries are sodium sulphur (Na-S) and zinc bromide (Zn-Br2) batteries which are being used in America as grid supply storage devices, (see Ref.83). These batteries have lower energy specific parameter than lithium-ion batteries but are much larger (a typical Na-S battery in these applications, for example, weights 100 tons) and are relatively cheap to manufacture. For railway applications these batteries are not suitable for onboard storage, but could be used on the trackside as energy storage devices, in particular for smoothing out peak load demands.

3.2 Super Capacitors Technology

In conventional capacitors, capacitance is achieved by separating two metal foil plates by a dielectric film. A super capacitor works differently. It achieves charge separation at distances of ion dimension by using carbon foil electrodes impregnated with conductive electrolyte. Positive and negative foils with carbon mush have an electronic barrier that is porous to the size of ions between them. The electrolyte materials are commonly propylene carbonate with acetonitrile, and quaternary salt tetraethyl ammonium tetrafluoroborate with activated carbon. Although some materials are toxic, generally there is no safety concerns as these materials are combined with other organic constitutes and are in low concentration.

The porous carbon provides an enormous surface area which is in the order of 2000 m^2/g. The ions are in meso and micro pores and accumulate in layers, resulting in an electric field within the electrolyte; this is known as an electronic double layer capacitor (EDLC). This phenomenon results in a capacitance that is somewhat voltage dependent.

This type of capacitor is also described as a symmetrical super capacitor since both of its electrodes are composed of the same porous carbon ingredients. A variant of the symmetrical, carbon-carbon super capacitor is the asymmetrical carbon-nickel super capacitor. The asymmetrical super capacitor is a pseudo battery and has a larger specific energy ratio than the symmetrical super capacitor.

Super capacitors have very fast pulse response times, because only stored charge is removed or restored at the interface, rather than reactions occurring in the bulk electrode material. This also results in super capacitors having a life cycle greater than that of electro-chemical cells, by orders of magnitude. Super capacitors are being designed and used to encounter millions of charging and discharging cycles throughout their useful life. The specific power of super capacitors is larger than 1,500 W/kg and the specific energy is approaching 6 Wh/kg. Both figures are continuously improving as the technology develops.

Super capacitors are superior to batteries when it comes to lifetime, deep DOD, operating temperature range, and power specific ratios. However the specific energy is poor compared with batteries. Referring to Figure 1 it is apparent from the Ragon plots that electro-chemical cells are orders of magnitude more capable than super capacitors in energy storage, but also orders of magnitude lower in terms of specific power capacity.

For a system level investigation the super capacitor can be modelled using a high level model such as that shown in Figure 9. Similar to batteries the efficiency of charging and discharging is affected by the equivalent series resistance (ESR). There is a limit to the maximum efficiency of a round cycle as the charging/discharging currents are constrained by the traction demands.

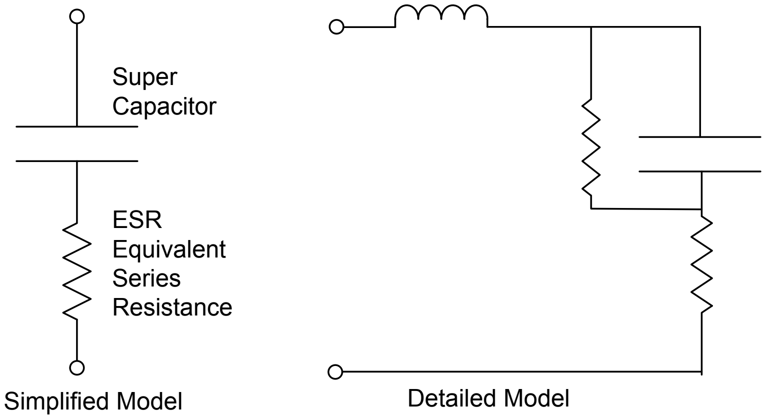


Figure 9 Simplified and detailed equivalent circuit of super capacitor

Super capacitors are currently manufactured in units having capacitances of several thousands, up to 10,000 Farads at relatively low rated voltages, typically 2.7V, (see Table 25). Consequently, for hybrid applications, banks of series-parallel combinations of super capacitor units must be connected to obtain the required voltage and power ratings.

The tolerance of super capacitors is usually ±20% and, as such, identical units may not have exactly equal capacitance. When connected in series, voltage mismatch results in lower capacitance units being exposed to higher voltage. To avoid this problem there are several equalisation schemes available. The most suitable for high-power applications are the fly-back converter cell equalisation method, buck-boost converter method, and forward converter method. All these methods employ power electronics circuitry, to balance the voltage across the different super capacitor cells connected in series, and this means additional weight and complexity.

3.3 Super Capacitors Combined with Batteries

Super capacitors in combination with batteries are a common architecture that utilises the energy storage capacity of a battery and provides the ability to deliver peak power during motoring, or capture regenerative power during braking, when using a super capacitor. The terminal voltage of the two devices during charging and discharging is not the same, as is shown in Figure 10. As such, separate, bi-directional, variable dc-dc converters of the type shown in Figure 26 are required.

Some successful trials have been conducted, which combined super capacitors and lead-acid batteries in hybrid applications. However, the advent of high specific energy and high specific power batteries, such as lithium-ion, would provide the required characteristics for energy and power simultaneously. Furthermore, using two storage devices of different terminal characteristics would require the use of separate controllers leading to further complications, higher weight, and additional cost.

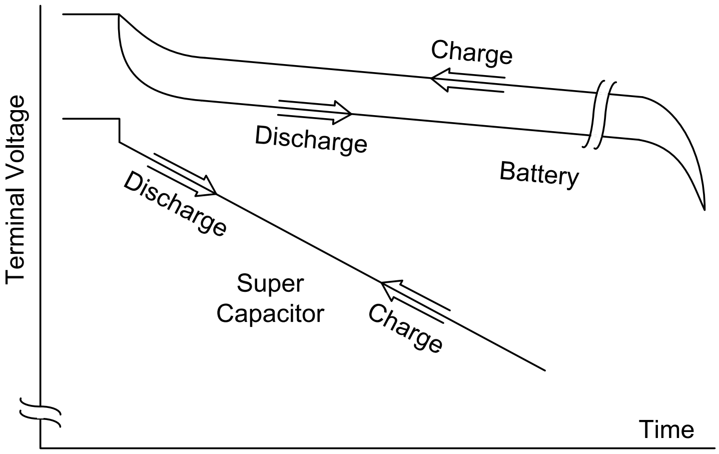


Figure 10 Comparison of charging and discharging of batteries and super capacitors

3.4 Survey of Batteries and Super-Capacitors

Appendix A contains a reference list of an up-to-date survey of batteries, super capacitors, hybrid systems, some mechanical storage systems, and general papers associated with the efficient use of energy on the railways. Table 13 to 26 of Appendix D provide useful information summarising the characteristics of batteries and super capacitors, and some mechanical storage systems, including indicative cost based on commercially published data. The data in Table 13 to 26 are self-explanatory and further details can be found in the references associated with each table.

The information presented covers the period from 2000 onwards, as these technologies are moving rapidly and information is continuously updated. It is important to consider the trends rather than the absolute levels, as there could be discrepancies between different published data. Many of the published data are of a commercial nature and may be somewhat biased. Discrepancies may also arise because of the interdependency of the different parameters presented such as the specific power and specific energy of different devices. Other discrepancies may be explained by the date of publishing the data, as the technology improves the parameters get better hence the same data published at different times would be different.

3.5 Performance Targets for Batteries and Super Capacitors

For there to be a practical railway application of batteries and/or super capacitors as energy storage devices, performance targets must be set for an intermediate term of five years. This period is roughly the timescale required for a full-scale implementation, should any of these technologies be selected.

The performance targets shown below are indicative and are expected to be achieved within the next five to ten years as the technology is progressing. It is conceived that none of the available devices today can meet all these requirements and as such these parameters must be considered indicative, and will only be used for comparison purposes in the studies that will follow in phase 2.

- Operating temperature -20 to 50ºC
- Specific energy ≥ 200 Wh/kg
- Energy density ≥ 300 Wh/L
- Specific power ≥ 400 W/kg
- Power density ≥ 600 W/L
- Cycling > 1,000,000 cycles
- Service life > 30 years
- Warranty interval 5 years or 250,000 mile whichever occurs first
- Price < £50/kWh
- Packaging in minimum of 50 kWh per pack

4 Flywheels and Hydraulic Systems

4.1 Flywheels for Energy Storage and Hybrids

Flywheels have been used to store and stabilise energy for hundreds of years. Early examples include the potter's wheel and spinning wheels. More recently advances in bearing technology, power electronics and vacuum enclosures have substantially improved their performance characteristics. The first modern flywheel systems were large stationary installations used to provide an uninterruptible power supply and the production of very large pulses of electricity for scientific or industrial use.

Only in the last two decades has flywheel technology been seriously considered for use in mobile applications. It was held back by prohibitive weight and unwanted precession forces. Both of these characteristics are determined by the specific tensile strength (the ratio of the hoop stress to material density) of the flywheel. Advances in carbon fibre composite technology have allowed the specific tensile strength to be greatly improved, leading to the development of light, high-speed flywheel systems.

Test vehicles, particularly buses, have been produced using mechanical flywheel systems with a continuously variable transmission (CVT) to transfer power to and from the flywheel. The next evolution was electrically-driven flywheels which do not require a CVT system thus avoiding added weight and reduced efficiency. Electrically-driven flywheels have another important advantage over their mechanically driven relatives in that vacuum integrity is easier to maintain, as no high speed mechanical seal is needed.

The electrically powered integral motor flywheel has been radically improved by incorporating magnetically loaded composite (MLC). The MLC was developed in the nuclear industry (see Ref. 63). Permanent magnets of the integral M/G are incorporated into the composite structure of the flywheel itself by mixing magnetic powder into the resin matrix. This has resulted in a reduced containment requirement, thus minimizing the overall weight of the system. Furthermore, in the event of a burst failure, the containment has to withstand only the crushing force of the composite material, which is far less than the load of discrete metallic fragments.

The magnetic particles in the composite are magnetised as a Halbach Array after the rotor is manufactured avoiding the need for backing iron to direct the flux. As the magnets in an MLC flywheel are comprised of tiny particles and there is no additional metal in the structure, the eddy current losses of the machine are significantly reduced. This can result in one-way efficiencies of up to 99%. The ultra-high efficiency means thermal management of the system is easier and it can be continuously cycled, with no detriment to performance or reduction in life.

With proper design and materials technology the modern „state-of-the-art" flywheel is a feasible energy storage device, it is non-polluting and has higher rates of energy storage and power input and release, larger P and E compared with conventional flywheels and even super capacitors, (see Figure 11).

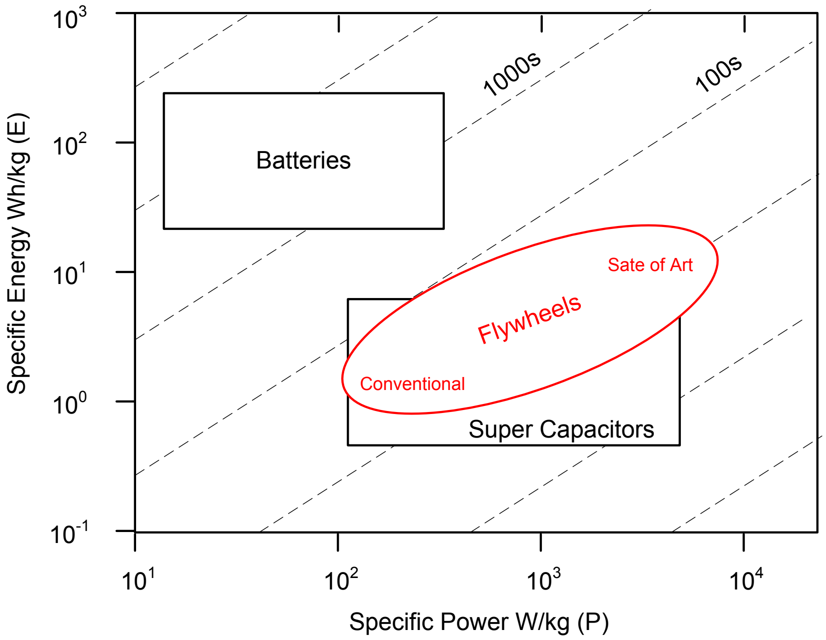


Figure 11 „State-of-the-art" flywheel Ragon plot compared with other storage devices

Flywheels have been fabricated with ratings of several hundred kWs and used experimentally on a number of railways, e.g. stationary flywheel units run, typically, at 37,000 rpm, and can provide power cycling of 250kW. Based on this technology, „state-of-the-art" mobile flywheel units based on MLC were successfully trialled on Formula 1 (F1) racing cars. Such devices operate at typically 40,000 rpm, max 55,000 rpm, and are capable of 120kW continuous cycling. However such flywheels are designed to have a limited life, for a few races or one season.

Moreover, CVT flywheel technology has been trialled on F1 racing cars. Many limitations of weight and gyroscopic forces have been overcome using a carbon fibre flywheel, thereby increasing the speed to typically 60,000 rpm. The flywheel is very much smaller and lighter than has previously been possible and the gyroscopic forces reduced significantly.

CVT flywheels are suitable to be integrated mechanically through CVT in parallel hybrid configuration and would be ideal for normal cars. The MLC flywheel on the other hand can be integrated electrically and would be suitable for rail applications in series hybrid. Furthermore the CVT is a mechanical device and conventionally CVTs are bulky and inefficient particularly when large power transmission is required, such as that for trains. Typical efficiency of a CVT flywheel is in the order of 70%, whilst an MLC flywheel"s efficiency is as high as 98%.

There is one main difference between the two flywheels:

- CVT is based on conventional kinetic energy storage where energy is transferred mechanically by the CVT.
- The MLC flywheel is based on transmitting energy electrically through MLC.

The latter process is much more efficient and would require less maintenance. In addition, integrating the MLC electrically with the onboard traction equipments is much simpler than mechanically integrating the CVT. The cost of MLC could be lower, as fewer mechanical parts are involved, and also MLC reliability and useful life could be better. In terms of safety both devices have the potential for catastrophic failure.

The energy stored in a flywheel is proportional to the square of its speed and as such if the speed drops, say from 55,000rpm to 37,000rpm, the stored energy drops by the square of the this ratio; that is, to less than half in our example. Consequently both the power and energy specific parameters, P and E respectively, drop by the same amount. Furthermore not all the energy stored can be used, as the minimum speed, practically, cannot be dropped to zero. In practice the minimum speed is typically around 50% of the maximum and subsequently the usable energy is 75% of the maximum stored.

The European Ultra Low Emission Vehicle – Transport Advanced Propulsion research project (ULEV-TAP 2), 2002-2005, (see Ref. 134), has undertaken development of a flywheel that runs at 22,000 rpm for diesel hybrid light rail vehicles. There are currently trials being conducted on the Spanish railways on the 3000Vdc systems using a conventional kinetic energy storage system (KESS) as static, trackside energy storage, (see Ref. 74). The technology of this system is based on a 3 ton steel flywheel run at a maximum speed of 2,600 rpm. Finally, a good example of flywheel applications in transport is the Parry People Movers, (see Ref. 140), used in small rail vehicles. The flywheel is based on conventional technology, weighs 0.5 ton, runs at 2500 rpm, and is installed on small rail vehicles.

Onboard (train) modern flywheel energy storage would have an additional advantage in terms of the ancillary circuits required. The power electronics circuitry is smaller and simpler compared with those used for batteries or super capacitors. The interface can be achieved using a standard 3-phase insulated-gate bipolar transistor (IGBT) inverter module, which could be identical to the traction module. Unlike batteries or super capacitors, there is no need for an additional transformer, necessary for the wide-range bi-directional dc operation to control the SOC in batteries or super capacitors. Refer to Figure 26 and Figure 27 for details.

However there are several technical challenges to modern flywheel energy storage devices including safety, reliability, the need for high power and compact packaging. Furthermore, robustness requires bearing-less in stationary applications at speeds up to 60,000 rpm and mechanical touch-down which is challenging task. In mobile applications ceramic bearings are used with innovative techniques to endure the extra high-speed operation and vacuum pressures as low as 1 m bar. The ceramic bearings, when used in a vacuum, must be lubricated with special vacuum grease. Alternatively the bearings may be moved outside the vacuum chamber and interface through a vacuum sealant. One of the problems created when operating a flywheel in a vacuum is removing the heat created by losses in the bearings and possibly electrical losses. A special gas/material may have to be used for this purpose, in which case even higher losses would be incurred.

4.2 Hydraulic Energy Storage Systems

Hydraulic hybrid systems are based on architecting hydraulic M/G and storage device in the post-transmission. Figure 5 illustrates the concept of hydraulic propulsion where the motor pump is connected at the transmission output shaft. Larger power densities and improved performance in hydraulic systems can be achieved by increasing hydraulic pressures. Hydraulic pressures of 5000-6000 psi (350-420 bar) are containable achieving power performance at levels of 500-1500 W/kg.

A hydraulic launch assist hybrid is a good example of hydraulic motor power applied to the propeller shaft. During decelerations the hydraulic launch assist accumulator is charged by a hydraulic pump driven directly by the vehicle"s propeller shaft. On acceleration the accumulator hydraulic pressure is discharged through the same motor, adding propulsion power or supplying the auxiliaries.

However, such a system operates at 350 to 420 bar and requires a substantial containment structure around the accumulator and motor / generator set, resulting in a larger weight and space requirements. Furthermore, the presence of two energy conversions sets an upper limit on system efficiency of less than 60%. The other issue with two energy conversions is the necessity to size the motor / generator set to the maximum power levels needed. The hydraulic accumulator still offers some advantages for railway applications because of its lifetime and the possibility of being charged and discharged very quickly and close to the limits.

Other storage systems which rely on dry nitrogen gas as a compressible medium and operate at hydraulic pressures above 6000 psi may be classified as pneumatic. These systems suffer from the same limitations of large containment requirement and poor efficiency.

The power specific P and energy specific E of hydraulic storage systems compared with other forms of storage devices is shown in the Ragon plots of Figure 12. Clearly the hydraulic energy storage suffers from poor energy densities compared with other devices.

The nano-titanate in Figure 12 is a modified Li-ion battery which is described in section 3.1.3. The specific power P may be considered to correspond to acceleration, and specific energy to correspond to range. Ragon plots provide a good indication about the power and energy capabilities, but what is not apparent is; the efficiency and useful life of the storage device.

Modern hydraulic systems are capable of capturing braking energy and store it in hydraulic accumulator. These systems can be installed on rail vehicles with a predicted fuel savings of typically 10% to 15%. Further advantage with these systems is that the diesel engine can be switched off as the train enters a station and the stored energy would enable an emission-free exit from the station.

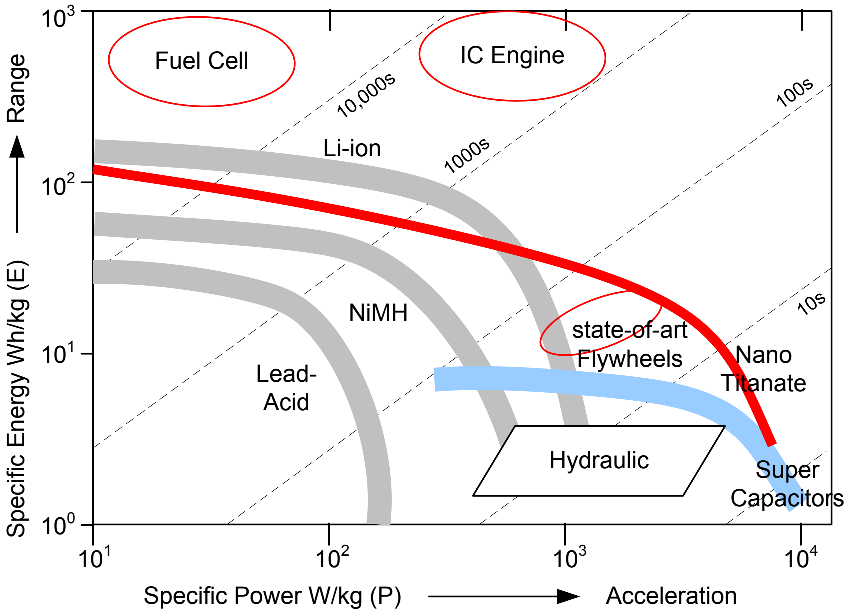


Figure 12 Ragon plots comparing hydraulic systems with other energy storage devices

5 Initial Investigation

The initial investigation under phase 1 is presented in this report. This covers a survey and applications of energy storage systems on the railway including diesel (and fuel cell) hybridisation, electric vehicles hybridisation and trackside storage applications.

The aim of this report (phase 1) is to provide a review of the current state and recent developments of energy storage devices. The analytical work involves a high level assessment of the requirements for each of the railway applications. These requirements will be assessed against the available energy storage devices, data, and possibly any future products which are currently under development. Phase 1 is basically the enabling work for the second stage of the project – phase 2.

5.1 Hybridisation of Rail Vehicles

Hybridisation of a rail vehicle may serve different purposes depending on the type of application. On diesel rail vehicles (DMUs) hybridisation has been introduced as a means to save energy by reducing the engine size, operating the engine at its maximum efficiency and recovering braking energy. On electric rail vehicles (EMUs) the main objective of hybridisation is to recover braking energy, and also there is scope to utilise the energy storage device to power the train through discontinuity in the supply, thereby simplifying and reducing the cost of the electrification. Electric vehicle hybridisation could be particularly feasible in cases where electrifying existing lines to 25kV ac standard incurs substantial civil engineering work or on dc railway, light rail vehicles can be operated for substantial distances through tunnels, heavily populated areas or complex junctions. Furthermore, in fuel cell rail vehicles, the main purpose of hybridisation is to minimise the size and power of the fuel cell and also to recover braking energy.

Hybridisation of rail vehicles aims at achieving one or more of the following:

1. Energy saving, reduction of CO_2 emission and reduced running cost.
2. Simplify electrification thereby reducing initial capital cost of electrification.
3. Improve supply performance by smoothing out loads and supporting line voltages.

Whilst diesel hybridisation is purely for energy saving, electric vehicle hybridisation may be utilised for both energy saving and power supply simplification. On specific dc routes, where gaps and weak power supply locations exist, all three aims could be achieved simultaneously.

For trackside applications (see section 5.2), both energy saving and improved supply performance can be achieved, particularly on dc.

This report presents an initial assessment of all these applications.

5.1.1 Hybridisation of Diesel Rail Vehicles

Diesel hybridisation is commonly realised by using a slightly smaller engine size than the full rated engine (or even using the same engine as designed for normal operation) and a relatively small storage device. This type of hybridisation will be called „mild-hybrid"(see Figure 3). For fuel cell applications the storage device is larger and the fuel cell rating would be slightly higher than the average power demand. This type of hybridisation will be called „power-assist".

A third type (see Figure 3) of hybridisation may be introduced when the power of the prime source is smaller than the average power demand, and a larger battery is used which can be charged externally. This type of hybridisation will be called externally-chargeable (also known as plug-in, in the automotive industry). Basically, the vehicle is battery powered with the addition of a small engine. This could be a relevant choice for a fuel cell demonstration vehicle, as reliability, continuity of operation, low cost, and demonstration of use of hydrogen as fuel are all required in a demonstration vehicle.

Electric vehicle hybridisation can be considered for all levels of hybridisation, mild (small storage), power-assist (intermediate storage), or chargeable battery (large storage).

Generally, hybridisation of railway diesel vehicles is of the parallel type shown in Figure 4, because the power and torque levels involved are relatively large. Diesel engines are usually most efficient within a narrow speed band and power output. Figure 13 shows the efficiency maps for a 2-litre diesel engine typically installed in a passenger car. This graph is for demonstration purposes, and could be representative of a DMU engine performance (typically 10-14 litres) with maximum engine speeds in the range of 1900-2100 rpm, and the peak torque region at about two-thirds of maximum engine speed (see Ref. 69).

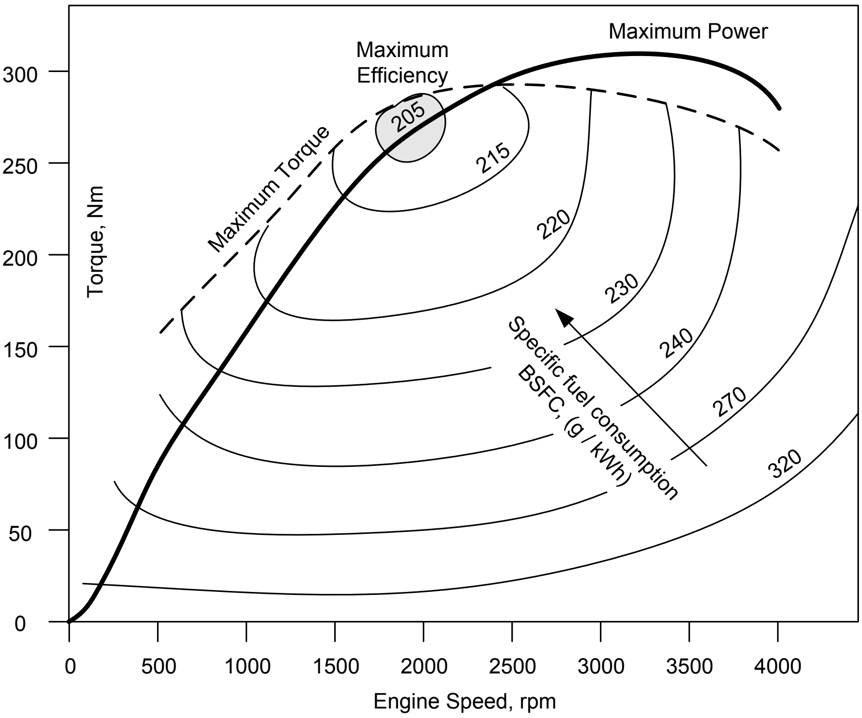


Figure 13 Typical efficiency maps of a 2 litres diesel engine

However, locomotive engines behave differently. These have lower speeds: typical medium engine speeds are in the order of 900-1000 rpm range and higher speed 1500 rpm. These have increased to 1800 rpm in later designs, which also has the effect of increasing the alternator frequency from 50 Hz to 60 Hz. The optimum operating point generally occurs when the engine is at full speed and power, rather than some reduced speed. Consequently, to obtain optimum performance it requires the engine to be sized correctly, so that it runs at full speed/load, rather than reduced speed. This is likely to have some benefit because lower capacity would burn less fuel at idle, although it would limit peak power, the solution for which would be to install multiple engines and shut some down when peak power is not required.

Regardless of the engine type or size, there is always a specific optimal point where maximum operating efficiency can be achieved. Therefore the concept of hybridisation is to maintain the diesel operation at or near that point and use a storage device to regulate the variable traction demand. The size and power capability of the storage device relative to the size of the diesel engine determines the level of hybridisation, which is an important factor to consider. For diesel engine applications, two options may be considered: mild-hybridisation and power-assist, as shown in Figure 3. In mild-hybridisation the diesel engine is run at its maximum efficiency but regularly switched off, particularly at the start of a journey and whenever the SOC of the energy storage device is full. Alternatively the engine may be left idle instead of switching it off since, unlike parallel hybridisation, in series hybridisation switching the engine on or off is relatively more difficult. In many cases of parallel hybridisation, particularly in cars, the engine is mounted directly on the drive gear making starting or stopping the engine much easier.

With engine power closer to average demand hybridisation becomes more of a power-assist type as shown in Figure 3. The required size of the storage device will be larger and the engine will be operating continuously at a near constant power and maintained at maximum efficiency. The frequency of switching the engine off will be lower. However, the closer to power-assist mode the more complex the energy management becomes. The energy management must match the engine power and SOC to the line characteristics and duty cycle. However this is not an easy task.

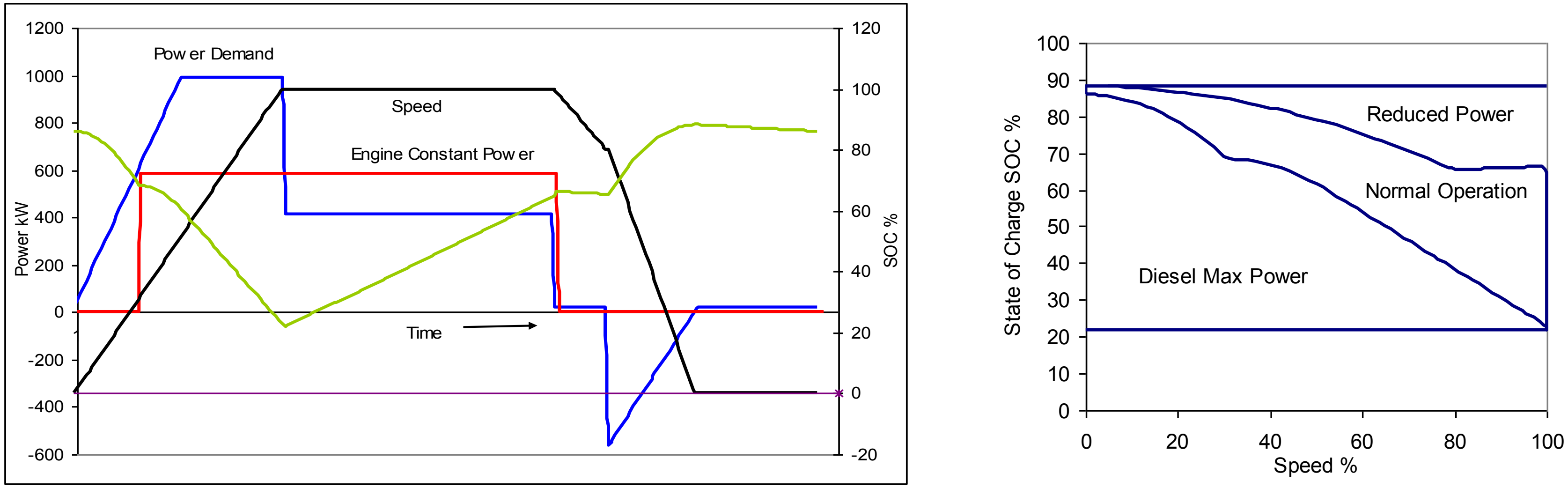
Figure 14 shows a simplified comparison of performance for two schemes, mild-hybrid and power-assist diesel rail vehicle hybrids. The diesel engine size is reduced by 34% between power-assist and mild-hybrid modes whilst the energy storage is increased by 57% to maintain the same performance.

The analysis presented in Figure 14 is very crude and further work will be required to determine precisely the level of hybridisation against the nature of service and duty cycle. There is a multitude of sophisticated diesel hybrid simulation tools in the market for this purpose. The most popular are ADVISOR (see Ref. 155) and PSAT (see Ref. 153).

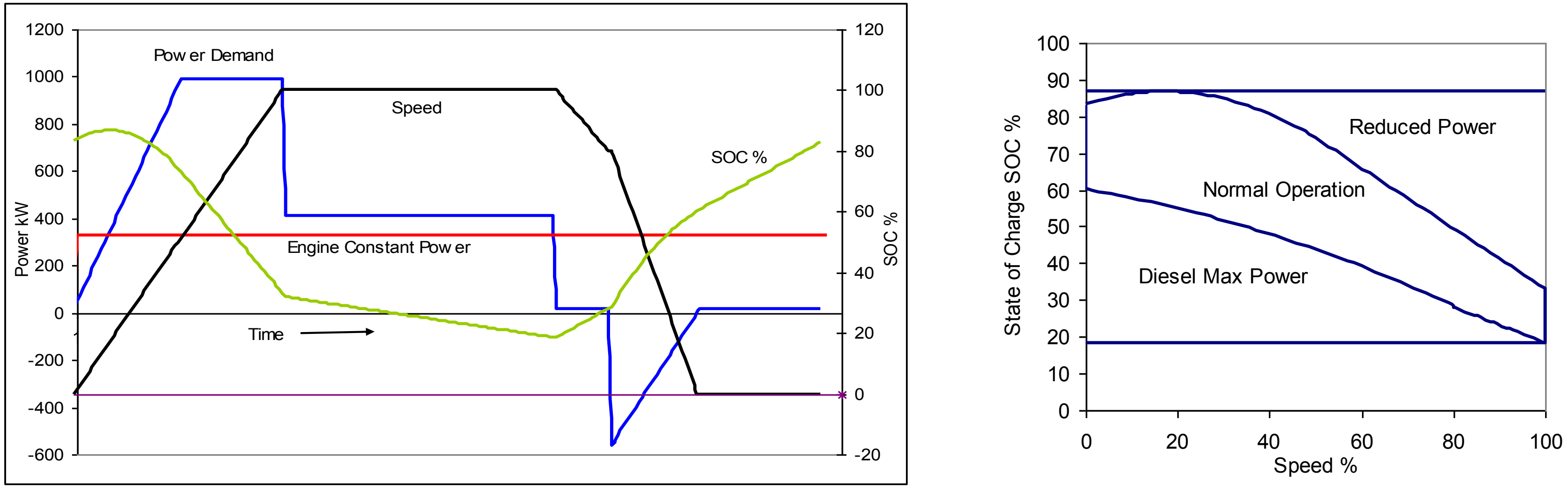
Generally, the level of SOC is controlled according to the train speed as shown in Figure 15. At higher speeds there is a large amount of kinetic energy available and the prospect of braking is more likely: therefore, the SOC is reduced. As such, a minimum level of SOC is maintained at maximum speed.

On the other hand the SOC is increased at lower speeds, and when stationary the SOC must be maintained at its highest level. Should the SOC reach its maximum level at minimum speed, the diesel engine must be switched off or kept idle.

The stored energy must be maintained within the nominal SOC-speed operating region for most of the time, for which the diesel operating point should be maintained at its maximum efficiency. If the operating point deviates outside the nominal region, the diesel engine power must be adjusted accordingly, at the expense of operating at lower efficiencies. The controller must be designed to minimise operating outside the nominal region to maximise the overall efficiency.



(a) Mild-hybridisation diesel hybrid



(b) Power-assist diesel hybrid

Figure 14 Comparison of performance for two schemes for the level of hybridisation of diesel rail vehicles

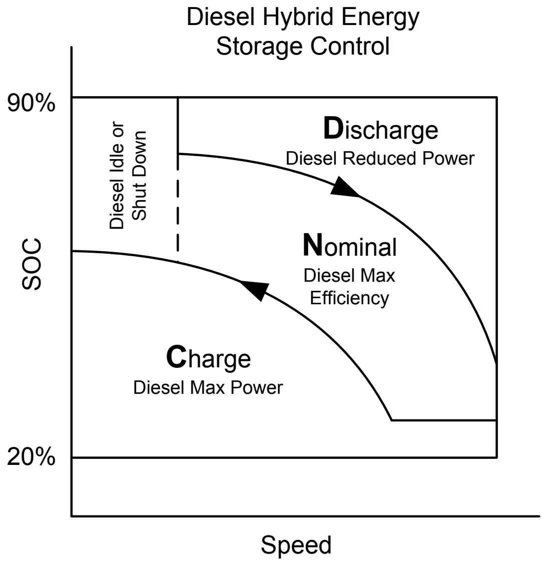


Figure 15 Charging and discharging control of an energy storage device in hybrid diesel vehicles

Energy saving in diesel hybrid vehicles is dependent on the nature of train operation. As the train dynamics and kinetic energy stored are well within specific limits, there is a close relationship between the way the train is operated and the energy wasted. The more energy wasted in operating the train, the larger the scope for saving and the more effective hybridisation becomes. Hence, diesel hybridisation is more effective if the train service is characterised by frequent variations in power and regular braking. A better energy efficient (EE) timetabling and service regulation results in reduced hybridisation benefits.

This is dependent on the type of train and duty cycle, and also depends on track layout and characteristics. Main line services with fewer stops are expected to achieve less energy saving in percentage terms than suburban with frequent stops. Reported energy saving in diesel hybridisation varies widely between 5% and 25% and even larger. For a given service, as allowance is added to the minimum journey time, there is a scope for introducing EE regulation and driving techniques, the result of which is to reduce the frequency of breaking intervals. Hence this results in reducing the prospect of energy saving in hybridisation. Figure 16 shows indicative figures.

Energy efficient (EE) driving is defined as the optimal speed-distance pattern in a station-to-station run, or distance between two stops. It depends on the profile of line speeds, traction characteristics, and maximum / minimum journey times, track geometry and gradient, as well as dwell time.

An EE regulation is a method by which optimum allowances are allocated to trains in complex areas, where conflicts at junctions are expected to occur.

An EE timetable is an optimised timetable that meets the service requirements and optimises the timings in such a way that EE driving can be introduced.

Currently, work is underway, in the UK and Europe, to implement EE driving, timetabling and regulation. This would inevitably mean a smaller scope for diesel hybridisation.

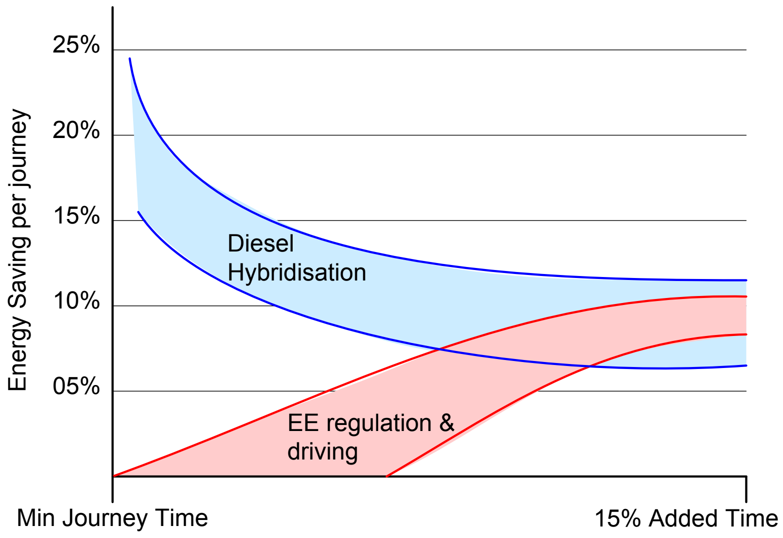


Figure 16 Relationship of hybridisation and EE timetable, regulation and driving techniques

5.1.2 Hybridisation of Fuel Cell Rail Vehicles

Hybridisation is driven by the cost of fuel cells. Generally, in power assist mode, the power of the fuel cell is chosen to be slightly higher than the average power demand,(see Figure 3). Alternatively, externally chargeable fuel cell vehicle may be considered where a much larger battery will be required and smaller fuel cell.

For a fuel cell to operate reliably, extensive auxiliary equipments are required to control the pressure, temperature and humidity precisely for different loading conditions. The output of a fuel cell can almost be considered as a constant voltage source for the required operating range, as shown in Figure 17.

Hybridisation of a fuel cell is similar to that of diesel and therefore will not be discussed further. Fuel cell vehicles are still in development and likely to be some time away, and therefore their application and use are outside the scope of this study.

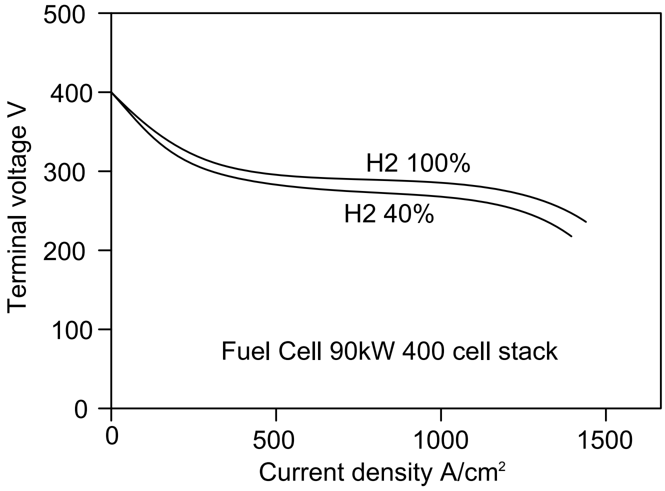


Figure 17 Terminal voltage of a typical fuel cell

5.1.3 Hybridisation of Electric Rail Vehicles

A train onboard energy storage device can be used primarily to recover braking energy particularly on dc railways. In addition the storage device can be used to power the train for short distances. This will bring about the possibility of introducing gaps in the power supply. Gaps may be appropriate when there are operational constraints, or could be utilised to reduce the cost of electrification, particularly in electrifying existing routes. Cost saving can be achieved by avoiding low bridges, narrow tunnels, complex junctions, station throats, etc. The relative merits of using train onboard storage devices is summarised in Table 4 for dc and ac systems.

	Function	
	Recover regenerative braking energy	Power the train through supply gaps
ac supply	Unsuitable as supply receptivity on ac is not an issue	Could be Suitable to simplify the OHL, thereby reducing cost, or when there are constraints on the OHL
dc supply	Suitable as the power supply is often non-receptive. System receptivity can also be improved using a trackside energy storage system or inverters	Suitable in specific cases for trams and urban trains operating in heavily populated areas. Gaps are not an issue on mainline railways

Table 4 Suitability of energy storage device for ac and dc electrification

Further application of onboard storage could be to smooth out power peaks if the energy stored is used in poor voltage regulation areas or at times where there is excessive demand. This application however is less important.

On ac systems, gaps in the OHL supply can simplify the design and reduce cost considerably if there are constraints in electrifying existing routes. It could be particularly realistic if the cost of civil engineering, such as raising bridges and widening tunnels, is prohibitively expensive. In addition gaps in the supply can be introduced in places such as junctions, cross overs, station throats, etc. which would further simplify the design and reduce cost.

An example is given in Table 5 where only 30% of the cost is required to electrify 80% of the line. This example presents an extreme case of electrification, the figures are indicative and used for demonstration purposes only. Further work on electrification is covered in T633.

For a 100-mile double track at an NPV cost of two million pounds per mile (£0.6 to £0.7 million per km per track has been reported) the total cost with discontinuous OHL would be 60 million pounds instead of 200 million pounds to electrify 80 miles. For a fleet of 60 trains the additional cost of the storage devices, say one million pounds per train, would be 60 million pounds. This would still save some 40% of the total electrification cost. Clearly, these are indicative figures only and further work will be required.

Type of Infrastructures	Percentage of Cost	Percentage of Total Distance
A	30	80
B	30	15
C	40	5
	100%	100%

Table 5: Cost proportions of different types of infrastructures (A) simple double track straight runs: (B) crossing, change overs, points, stations, sidings, level crossing, etc., and (C) raising bridges, tunnels widening, route diversions, etc.

The scheme could improve safety, since electrified lines are removed from complex areas. Also, reliability could be improved as there is a lower probability of dewirement, short circuits, etc., particularly in areas such as bridges, tunnels, crossings, etc. There are, however, a number of issues related to this scheme, such as introducing the practice of raising and lowering the pantograph regularly and the consequent safety and reliability implications, and also the risk of trains being stranded at gaps.

The assessment at this stage is speculative as it assumes less live equipment is desirable. However frequent pantograph raising and dropping on the move plus power down operations will potentially add technical and safety risks. Separate studies (T777 and T778) to address these problems are being undertaken, therefore no further investigation will be carried out in this project.

A gapped-supply scheme is equally viable on dc supplies particularly for light railway urban services (Ref. 121) in places where electrification may present problems, e.g. level crossings, heavily populated regions, conservation areas, limited clearances, etc. This is in addition to the obvious advantage of using the energy storage device on dc to recover braking energy where receptivity of the supply is usually problematic.

A train onboard storage device may be sized according to the nature of discontinuity in the supply and type of train.

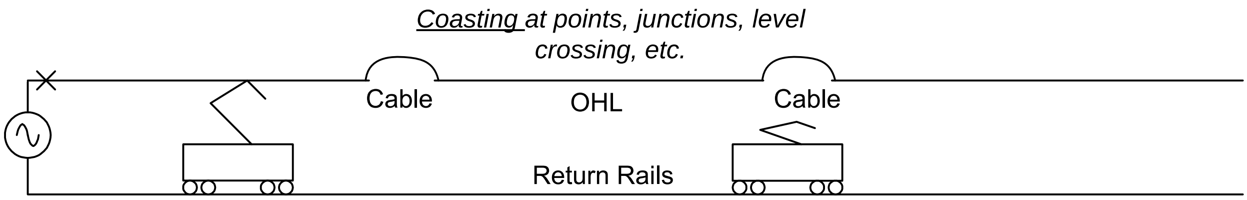
There are three electrification schemes to be investigated as part of the drive to minimise electrification cost, these schemes are as follows (see Figure 18);

(a) Short distances of a few 10s of metres where „coasting" can be introduced and no storage device will be required.

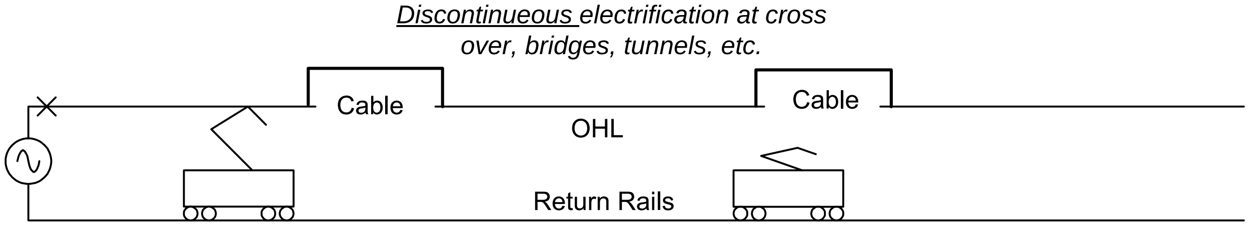
(b) Gaps of distances in the order of a few 100s of metres where small storage devices, e.g. super capacitor, can be used to provide power for short durations through discontinuities such as cross overs, junctions, level crossings, brides, etc. This scheme will be called „discontinuous" electrification.

(c) The last scheme is to use an energy storage device to power a train for substantial distances, in the order of a few km, on non-electrified stretches of the route. The storage device in this case would clearly be a battery. This scheme will be called „discrete" electrification.

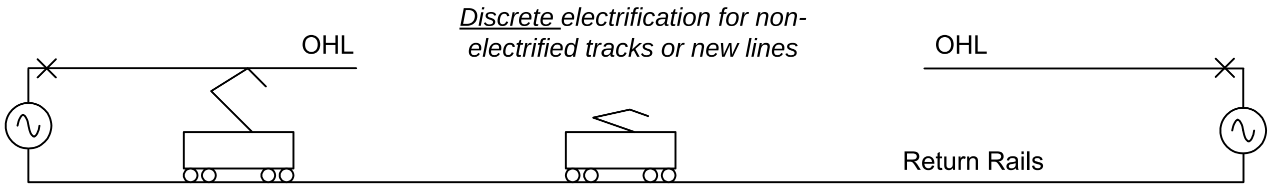
Section 6 provides a comparison between two energy storage design examples for discontinuous and discrete electrification schemes. Discrete electrification may be applied to lines linking two electrified routes, tracks running through complex areas, or where electrification poses difficulties.



(a) Coasting, no energy storage device required


Discontinueous electrification at cross over, bridges, tunnels, etc.
Cable
Cable
OHL
Return Rails

(b) Discontinuities electrification, size of storage device determined by power requirement


OHL
Discrete electrification for non-electrified tracks or new lines
OHL
Return Rails

(c) Discrete electrification, size of storage determined by energy requirement

Figure 18 Two different schemes of discontinuous power supply on the railway

Gaps in the supply can also be implemented in BT and AT systems. Figure 19 shows the arrangement for a discontinuous scheme in AT systems. However for the case of discrete electrification, because of cost, it is improbable to use an AT system fed from 400kV.

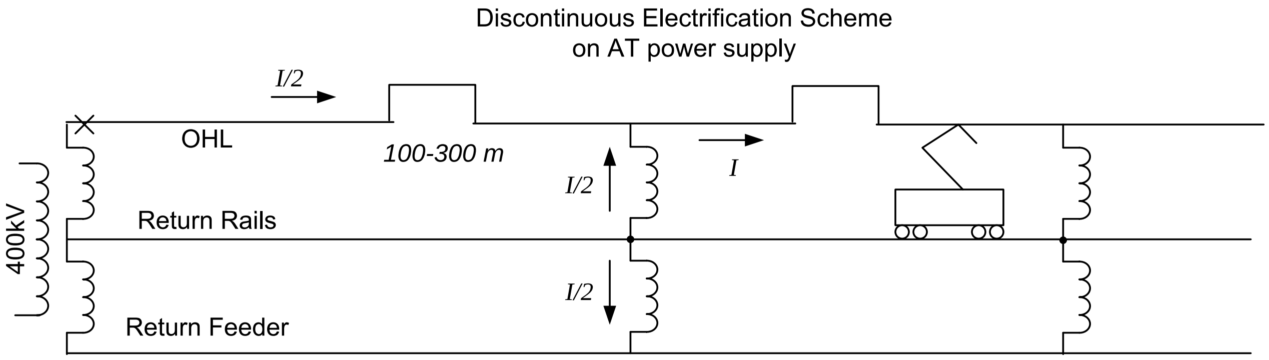


Figure 19 Different schemes of discontinuous and discrete AT supply systems

In hybridised electric rail vehicles the SOC controller of the energy device must ensure, depending on its application, that both purposes of recovering regenerative braking energy and powering the train through gaps are met. Whilst for the purpose of storing braking energy the SOC must be kept at its lowest state possible, powering the train through gaps requires that the SOC must be kept sufficiently high to supply the required power.

Therefore, to achieve both purposes, the SOC must be maintained at some quiescent point which is speed dependent. Since the kinetic energy of the train is higher at higher speeds, the SOC must be lowered to allow for storing of the braking energy, and vice versa at lower speeds. As the kinetic energy is lower and it is less likely that braking is applied, the SOC must be increased to a sufficiently high level to enable the train to operate through supply gaps.

Controlling the SOC therefore must be speed dependent and the ratio of the SOC to train speed must be inversely proportional. Moreover the ratio of SOC to speed during motoring must be higher than during deceleration, and in both cases the ratio is inversely proportional. Figure 20 shows a simplified speed-distance mapping of a station to station journey on discontinuous supply. Figure 21 shows the corresponding relationship between the SOC and train speed. Both figures are shown for demonstration purposes.

Figure 21 also shows that the SOC drops below the minimum specified level of the storage device. In the case of a battery this will considerably reduce its life. In comparison a super capacitor can tolerate a considerably larger number of cycling at deep discharge and therefore its life is considerably longer. For flywheels, the number of deep cycling is even larger than super capacitors. However, the flywheel would require regular servicing and maintenance unlike super capacitors. The useful life of a super capacitor and flywheel may be comparable to the life of the traction equipment and could be in the order of 20 years.

If only one function, either recovering regenerative energy or powering through gaps, is required, then the SOC controller would be much simpler. If the function of recovering regenerative braking energy alone is required, then the SOC must be kept as low as possible all the time, and vice versa, for powering the train through gaps.

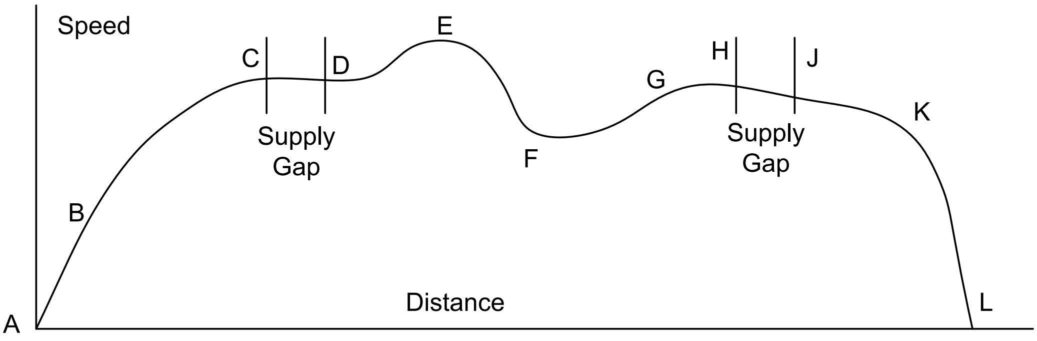


Figure 20 Simplified speed distance journey on a discontinuous supply.

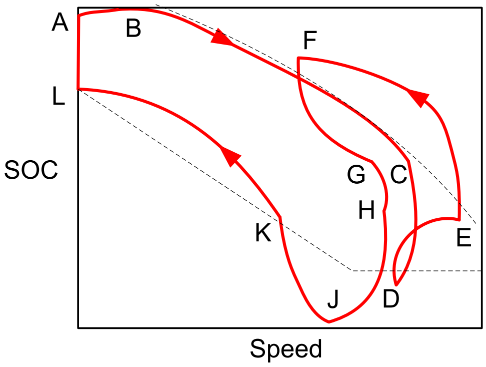


Figure 21 Charging and discharging over a complete duty cycle of Figure 20

The general criterion of the storage device SOC versus speed in HEV may be expressed in the relationship shown in Figure 22. In a practical application the controller should also link and match the rolling stock characteristics to the infrastructure characteristics including discontinuities in the supply. Optimisation of such control will only be possible using a system-wide simulation proposed in phase 2 of the project.

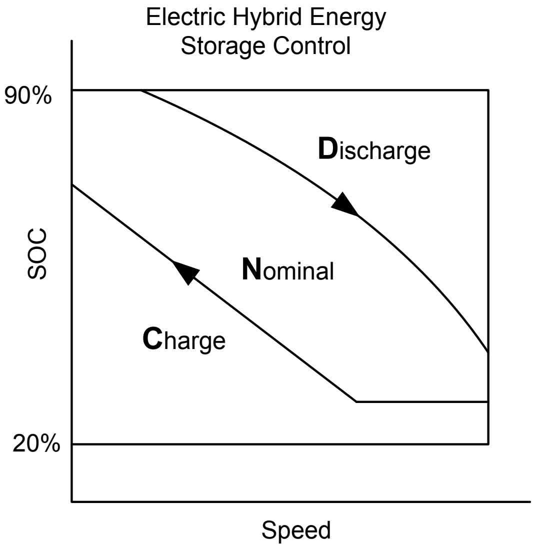


Figure 22 Generalised control scheme for charging and discharging the energy storage device on Electric Hybrid Vehicles (HEV)

5.2 Trackside Energy Storage Applications

Stationary energy storage devices are being used in industrial transmission and distribution power networks in a few places around the world, particularly in the USA. Among these devices are compressed air energy storage, flywheels, batteries (mainly Na-S and zinc bromide), super capacitors, and superconducting magnetic energy storage (SMES).

On the railways, and particularly on dc, devices such as flywheels, batteries and super capacitors have been used and tested. Also, inverters were used to recover regenerative braking energy. In trackside applications, there is relatively less constraint on weight and size compared with the train onboard energy storage applications and therefore there is a wider range of choice. Also, in practice, it is relatively easier to implement and test a trackside energy storage device compared with a train onboard device.

Trackside applications on the railway are only suitable for dc electrified lines, since ac systems are inherently receptive and ac voltage levels are much larger. The following discussion therefore focuses on dc only.

In terms of load flow, dc electrified systems generally suffer from a number of problems, these can be summarised as:

(a) Poor receptivity to regenerative braking energy.
(b) Poor voltage regulation particularly in long feed sections and relatively low line voltages.
(c) Load fluctuations which may result in peak power demand that is considerably larger than average.
(d) Higher losses compared with ac, not only transmission losses, but no load losses in transformers and insulators along the tracks.
(e) Problems with stray currents leakage in ground and metal structures resulting in corrosion and damage to steel bridges, tunnel linings, etc.

Receptivity of the system depends on several parameters, including density of the train service, traction characteristics, permissible upper limit of the line voltage compared to nominal voltage, track profile and length of feed sections.

Voltage regulation is governed by distances between substations and the capacity of the power plants to meet peak power demands. Peak demands normally happen during peak services and would coincide with the probability of a number of trains simultaneously motoring. There is also the probability that a number of trains simultaneously re-generatively braking. This last occurrence would have two effects: first it increases the frequency of large power swings, resulting in larger load fluctuations between maximum and minimum demands, second it converts the system to a state of non-receptive where regenerative braking energy cannot be recovered.

To address many of these problems energy storage devices can be very effective if used on the trackside, particularly when combined with other systems such as Voltage Controlled Rectifies (VCR) and/or inverters. Figure 23 shows an example of storage devices used with VCR / inverter substations. This scheme is capable of recovering most of the regenerative braking energy, minimising losses, improving voltage profile and smoothing out peak demands. Ref. 92 describes a pilot scheme employing VCRs and inverters along with storage devices on La Rochelle LRT test track in France.

Another scheme is to design an equivalent AT system for dc railways as shown in Figure 24, (see Ref. 93). To convert a conventional dc system to this scheme requires the installation of an additional negative feeder that is fed from rectifiers installed at the substation and feeding negative voltage with respect to the rails. It also requires power electronics-based equipments that are equivalent to auto transformers in AT system installed at regular distances between successive substations. These devices ensure current balance between the positive and negative feeds. Such a system will enable much wider distances between substations thereby possibly reducing cost. Furthermore, the negative feeder could be operated at higher voltage levels which would enable even wider a part substation distances. Such a scheme would be equivalent to a HV dc distribution system which could even replace the 3-phase HV supply.

VCRs may also be used to minimise touch potentials and stray currents in dc systems. This can be achieved by regulating the line voltage to redistribute traction currents in the rails in such a way that reduces the rail to earth potentials. A variation of this design is to use smaller VCR operating at low voltage to circulate current in the running rails that counter the effects of traction currents.

The impetus of such designs is to utilise the capabilities of modern power electronic systems to improve the performance of dc systems. One possible application is to integrate the protection of dc power supplies within the electronics controller thereby eliminating bulky dc circuit breakers.

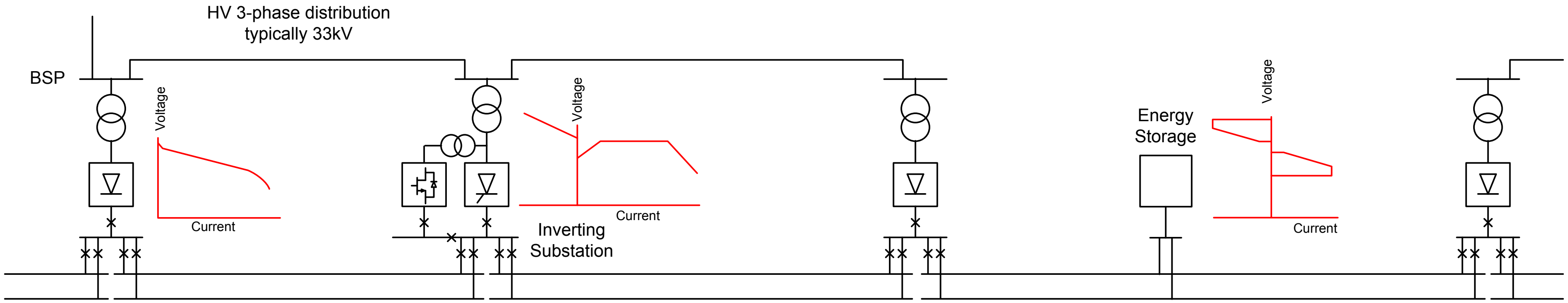


Figure 23 Typical dc electrified railway deploying inverters and energy storage devices

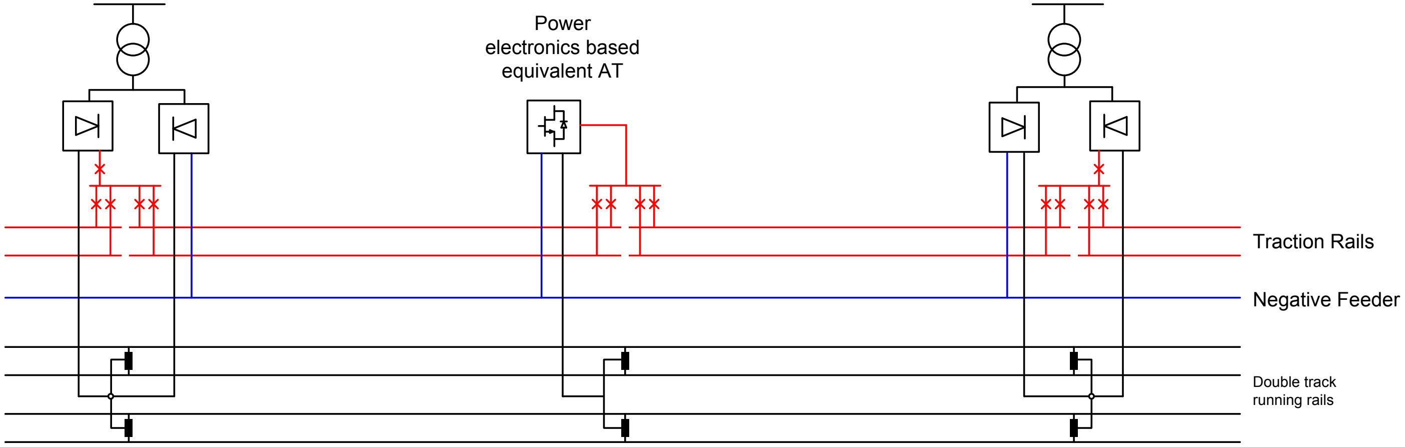


Figure 24 Equivalent AT dc traction supply scheme

A trackside storage device on dc railway can be controlled mainly by monitoring the line voltage. To support recovering regenerative braking energy and reduce peak power demands the SOC must be maintained at an operating point that corresponds to the nominal range of line voltages. As the line voltage increases, usually due to one or more trains regeneratively braking, the excess power is stored in the device leading to an increase in SOC. On the other hand, during peak load demands the line voltage will drop and consequently power is pushed back into the system, resulting in a reduction of the SOC. Figure 25 shows a generic mechanism that achieves both purposes of storing braking energy and providing power during peak demands.

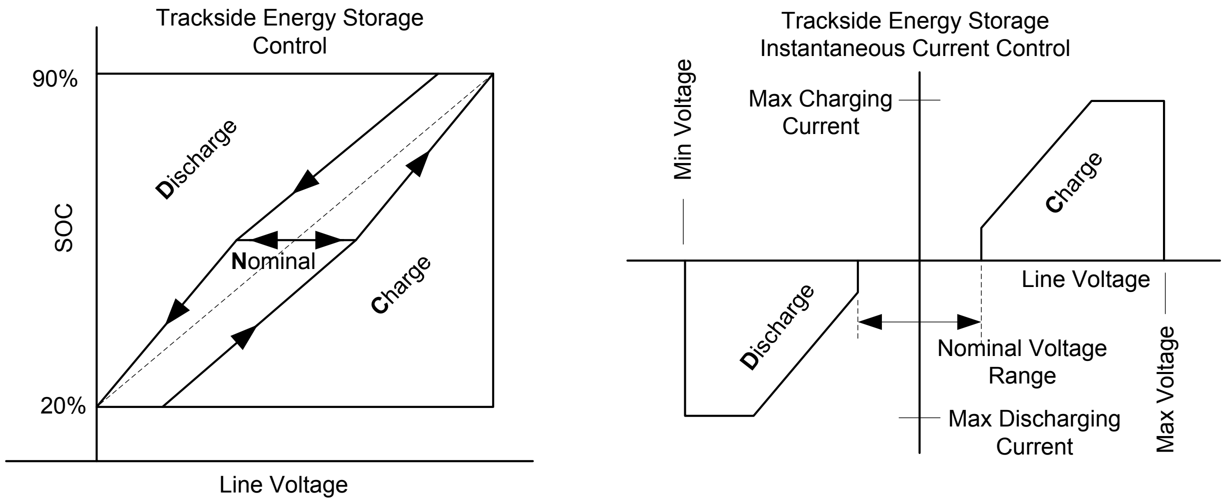


Figure 25 Control scheme for charging and discharging of a trackside energy storage system

In practical applications, detail of the system infrastructures, train traction characteristics, number and locations of storage devices must be considered in a system-wide simulation to optimise and size the storage devices numbers, locations, capacities and control mechanisms. This should be preceded by characterising the system by taking measurements of line voltages and profile of traction currents before introducing the storage devices.

5.3 Battery Powered Rail Vehicles and Applications

Battery powered rail vehicles are in use in specific environments such as service trains in tunnel sections of the type used by LUL. There are many other applications for these vehicles such as fork lifts where the requirements for emission and noise free environments are a must. Other applications include the use of batteries for emergency operation, UPS systems and temporary storage systems.

The advent of high efficiency, longer life, faster charging and discharging rates and high specific energy and power densities of new batteries, such as NiMH, Li-Ion, Na-NiCl, Na-S and Zn-Br2, compared with the conventional lead-acid battery would improve performance of these applications. The specific energy density of a Li-ion battery, for example, is three to four times that of a lead-acid battery and consequently, for the same weight, a Li-ion powered EV would have to be three to four times the range of that powered by a lead-acid battery.

The key design aspects in any of the applications above is to optimise the operating time, charging time, level of DOD and the consequent useful life, weight and volume of the battery. All these parameters will determine the appropriate size and type of the battery for a given application. Compared with hybrid applications the battery would have a much shorter useful life if used as the main source of energy because the levels of DOD will be higher and more frequent.

There are two main issues to consider when batteries are used as the main source, cost and useful life. Whilst new batteries promise better performance, longer life, smaller weight and volume their cost is considerably higher than conventional lead-acid batteries. Furthermore some of the new batteries require rather sophisticated management systems which further add to cost and complexity.

6 Design of Energy Storage Systems

In section 5.1.3, two energy storage systems of different performance characteristics were suggested, one for small distances of a few hundred metres (discontinuous electrification) and the other for relatively longer distances of a few kilometres (discrete electrification). For small distances a short duration burst of power will be required which would be achieved by a super capacitor or flywheel. For the longer distances sustained energy storage will be required for a substantial time. This would be achieved by a battery. Two electrical schemes, a super capacitor and battery, are described in sections 6.1 and 6.2 respectively. These devices are available commercially.

Section 6.3 presents a feasibility study for developing flywheel storage which would be suitable for a train onboard discontinuous electrification. If the performance targets of such a device are achieved it will outperform super capacitors by large margins. Section 6.4 provides a brief description of hydraulic storage and section 6.6 compares different types of storage devices.

6.1 Super Capacitor Energy Storage

Super capacitors are usually manufactured in cells having capacitance of up to 10,000 Farads and operate at voltages between 2.5V and 3.0V. High power modules are also commercially available.

The specifications of commonly available capacitors are shown in Table 6, (see Ref. 116). Also refer to Table 25 for detailed specifications of selected a Maxwell cell and module. The current limit for these capacitors is 400A-600A. The number of cycles is more than one million, giving a useful life of up to 20 years based on an average deep DOD of 100 a day.

Different Types of Super Capacitors	Weight Per cell (kg)	ESR (mΩ)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Cell Voltage (V)	Time Constant (τ=RC)
1	0.65	0.25	2.31	7284	3	0.65
2	0.34	1	1.3	6618	3	1.2
3	0.52	0.6	2.5	8929	2.5	1.6
4	0.4	0.6	2.49	7812	2.7	1.8
5	0.21	2.1	27	8000	3.8	6
6	1.5	4.4	60	540	3.8	200

Table 6 Specifications of different super capacitor types.

For high-power applications, such as the presented scheme, it would require a combination of series and parallel cells to obtain the required voltage and power rating. Adding cells in series increases the voltage rating, but reduces the capacitance. To increase the capacitance parallel branches are added.

The tolerance of these capacitor cells is ±20% and therefore connecting them in series may result in that cells with lower capacitance being subjected to higher voltages, which may result in damage. To operate reliably an additional balancing, monitoring and thermal management systems are added. This results in additional cost, size and weight. Furthermore, for hybrid applications a bi-direction wide-range dc-dc converter is required to control the SOC. The weight of this converter is determined by its power. A commonly acceptable figure of 5kW/kg is usually used for this purpose.

A typical 4-car EMU would have two motor cars, each motor car has two inverters and each inverter drives two motors. Each motor is typically rated at 250kW giving maximum total power of 2MW.To operate this train for distances up to 500m at an average speed of 60 kph a continuous power capability of 1MW for up to 30 seconds would be required. To meet this demand the theoretical weight of super capacitor cells alone, without the balancing, monitoring or thermal management systems or packaging would be in the order of 2 tons for 100% energy storage. The corresponding volume is about 7 cubic metres at a current cost of around £55,000. These figures are based on a nominal specific power of 500W/kg, nominal specific energy of 6 Wh/kg, volume at an energy density of 1.7 Wh/L and a target cost of 1 cent per Farad for more than 1 million units purchase. The cost of development is not included.

In this outline design (namely Cap-A in Table 9) the super capacitor is providing 1MW continuous power for 30 seconds to a typical 2MW 4-car train. Clearly the main function of the storage here is to power the train through gaps, it is not designed to provide maximum power. However to assess the train performance against the available energy stored a system-wide investigation, incorporating the infrastructure characteristics, will be carried out in phase 2.

In practice the capacitors must be designed to be integrated with the traction packages individually. In a 4-car train there are typically four traction packages and therefore the same number of capacitor modules will be required. It should be emphasised that the aim of this exercise is to size the capacitor, it is not meant to be a detailed design.

Super capacitor modules that meet a demand of 1MW for 30 seconds will have higher weight and will cost much more. For example, a large super capacitor module, that is commercially available, is typically rated at 125V, 63 Farad weighs 59.5 kg and costs around £3,000. To meet the 1MW-30s demand, 60 modules will be required (possibly 10 branches in parallel, each having 6 in series) at a total weight of 3.6 ton and a cost of £200,000. However, the volume is reduced to 5.3 cubic m. If the converter weight is added, the total weight would be in the order of 4 ton.

The specific power of super capacitors can be considerably larger than 500 W/kg as used in the example above. For a 1000 W/kg the size of the super capacitor can be halved for the same power, but for half the duration. The overall weight, volume and cost however do not reduce by the same ratio because of the additional circuitry required. It is estimated that, for the same power, when a 1MW-30s capacitor is halved to 1MW-15s the weight (Cap-B in Table 9), volume and cost would be reduced by the amounts shown in Table 7. These figures are approximate estimates and should only be used as indicative. Note in all these estimates the cost of development is not included which could be substantial.

Consider the 1MW-15s device, the energy required to be delivered is 4.16kWh (1MW for 15 seconds). This is the usable energy. However, the total energy stored is larger since the energy is proportional to the square of voltage and, practically, the operating voltage cannot be controlled down to zero. As such for, say, half the operating nominal voltage the usable energy is 75% of stored energy. If a 2700F cell from Table 6 is chosen, then to deliver a usable energy of 4.16kWh at 75% of the total stored energy the number of cells required will be around 2220, given the specific energy is 2.5 Wh/kg. To operate at voltages between 550V and 1100V, then 2220 cells may be divided into 5 modules having 444 series cells in each. This produces a nominal operating voltage of 1,110Vdc. This system will be capable of delivering instantaneous power well above the 1MW required. The overall ESR is 53.2 m.Ω, which gives 92% efficiency at full loading discharging of 1MW and a round efficiency of 85%. The maximum losses and heat dissipation is 76kW. At half loading of 500kW the efficiency would be 96% and round cycle efficiency of 92%. These figures are indicative and clearly further work will be required to optimise the series/parallel combination, voltage levels, losses, etc.

This system will be capable of delivering the 1MW power required but it will have poor energy storage capability. To maximise the benefits of a storage device the preliminary design may be modified to a smaller device, thereby minimising its weight and maintaining the power required at the expense of stored energy. For example, if the five modules system containing 444 series cells each is re-configured using three modules (or four if using one module per traction package) instead of five then its energy storage capability will be 1MW-9s (Cap-C in Table 9), or 2.5kWh (3/5 of 4.16), its weight will be 1.8 ton and volume 3 cubic meters, (see Table 7). The continuous 1MW power capacity will still be met, given that the 2700F unit in our example has a power specific of 8929 W/kg.

Super capacitors are usually manufactured to have much higher specific power than 500 W/kg and lower specific energy than 6Wh/kg. Like batteries the two parameters can be modified at the expense of each other. So, to maximise the instantaneous power capability the electrodes, for example, will have to be designed to withstand larger currents but this is at the expense of allowing smaller energy storage content. However, unlike batteries, with super capacitors there is no constraint on the power capability and as such there is greater flexibility to optimise the specific power against specific energy in the final design.

Energy	Weight	Volume	Cost	Range	Code (Table 9)
1MW-30s (8.33kWh)	4 ton	8 m^3	£200k	500 m	Cap-A
1MW-15s (4.16kWh)	3 ton	5 m^3	£120k	250 m	Cap-B
1MW-9s (2.5kWh)	1.8 ton	3 m^3	£75k	150 m	Cap-C

Table 7 Comparison of different super capacitor options

Clearly with super capacitors the power requirement is not a problem. However the poor energy specific levels mean that the durations of required power pulse must be minimised in order to optimise the design. The implication of this for EHV would be to shorten the supply gaps such that a smaller and more optimised super capacitor storage device can be designed. The optimum design is system dependent and should be investigated in a system-wide approach that incorporates the railway infrastructure, train parameters and operating conditions.

6.2 Lithium Ion Battery Energy Storage

For longer distances and for the same train type, 4-car EMU, the requirement would be to supply continuous 1MW power for up to 10 minutes. Given that the specific energy of a lithium ion battery is typically 120 Wh/kg and the specific power is 250 W/kg then at 35% DOD a 4 ton worth of lithium ion battery cells, without the necessary ancillary circuits, would meet the requirements [1] of continuous 10 minutes 1MW power (see Bat-A column in Table 9).

Lithium ion batteries are manufactured in cells and high-power modules, an example is given in Figure 27. The total volume of the battery, given that the energy density is 150 Wh/L, would be in the order of 3600 litres or 3.6 cubic metres. For shallow cycling, and in order to lengthen the battery life, the duration may be reduced to five minutes resulting in a reduction in the DOD by the same amount, to about 17.5%, and this is sufficient to power the train for distances up to possibly 5 km at an average speed of 60kph (see Bat-A column in Table 9). Given the cost metric for Li-ion batteries, defined per Wh, as around $0.5 at 2007 prices, the total cost would be around $240,000 for 4 ton lithium ion battery cells alone.

The cost, weight and volume quoted do not include design, packaging, the energy management system or balancing circuit, if required, or the cost of power electronic circuitry such as the bi-directional dc-dc converter. If, for example, a battery is built from a number of high power modules that are commercially available then the cost would be over £1.3 million. Clearly, for a hybrid application, such as that presented, a high-power battery is designed by connecting a combination of series and parallel cells in the same fashion as that shown for the super capacitors. Hence the overall cost would be the cost of the cells plus the additional power electronics circuitry, management system, monitoring system and packaging. An indicative figure would be approximately double the cost of the lithium cells, which is in the order of £250,000 to £300,000 (noting the differences and fluctuations in currencies). However, it is expected that the cost of lithium ion batteries will go down in the next few years.

The weight of the battery in the outline design shown above is determined by the continuous 1MW power for a 10 minute requirement. The base line assumed parameters in this design are: maximum specific power 250W/kg and maximum specific energy 120Wh/kg at maximum 35% DOD. This would produce a useful life of around three years.

An alternative design of a smaller size battery that is power orientated and has a smaller energy storage capacity will be based on a larger specific power of 400W/kg, and a lower specific energy of 80Wh/kg (see Bat-B in Table 9). Such a battery will provide the required 1MW power, but it stores lower energy. At 41% DOD this battery will provide continuous 1MW power for five minutes. However, the expected useful life will be in the order of two years. This battery can also be run for shorter durations, thereby increasing its useful life.

Batteries are usually optimised by designing the specific power and specific energy against the application required, e.g. EV or EHV. The two parameters are related as shown in Figure 1 and Figure 12. For example, to maximise the instantaneous power capability the electrodes will have to be designed to withstand larger currents, but this is at the expense of allowing smaller energy storage content.

The presented figures are based on commercially currently available Li-ion batteries. However the technology is improving continuously, e.g. nano titanate. It is expected in a few years that higher performance Li-ion batteries will be available at lower cost.

The presented batteries are designed to deliver continuous 1MW power to a 2MW 4-car train. Clearly the main function is to power the train through gaps, not to provide maximum power. Therefore to assess the train performance against the available energy stored a system-wide investigation, incorporating the infrastructure characteristics, will be carried out in phase 2.

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[1] For comparison purposes an equivalent conventional lead-acid battery would weight nearly 3 to 4 times the equivalent lithium-ion battery.

Similar to super capacitors a practical battery must be split into several modules that can be integrated with the traction packages individually. In a 4-car train there are typically four traction packages and therefore the same number of battery modules will be required. The aim of this exercise is to size the battery, it is not meant to be a detailed design.

6.3 Flywheel Energy Storage

Flywheels are capable of cycling relatively large power for short durations and as such their performance may be compared with super capacitors. Conventional flywheels utilise heavy steel mass rotating at relatively low speeds of around 2,500rpm. These flywheels perform poorly compared with super capacitors in terms of specific power capabilities and heavy maintenance requirements and as such they do not compare favourably.

However the advent of MLC flywheels with an integrated electrical motor, described in section 4.1, has radically improved the performance of the flywheel as an energy storage device. Ref. 64 outlines a feasibility study into a 650kW power device which would be suitable for railway applications, particularly for train onboard storage. This design is based on a typical 120kW flywheel which is being trialled and tested successfully on F1 racing cars. The design parameters and specifications of the proposed unit are shown in Table 8.

Parameter	Value
Maximum Stored energy	36MJ (10 kWh)
Usable Energy	27MJ (7.5 kWh)
Max Continuous Power	650kW
Max Flywheel Speed	36,300 rpm
Flywheel Mass (including containment)	400kg
Flywheel Casing Outer Diameter	520mm
Flywheel Casing Length	630mm
Flywheel Volume	140 Litres (0.14 m^3)
Ambient Operating Temperature	-40C min 55 C max
Cycle Life	10,000,000 cycles

Table 8 Outline design parameters of a theoretical MLC device that can be used on a train

This device would be suitable for integrating with the train traction package and incorporated with the traction inverter and dc link filters as shown in Figure 27. A typical 4-car EMU would have multiple inverters with each inverter normally feeding two traction motors[2]. The traction package is generally rated at around 500kW. However there are different configurations in use, e.g. Class 390 has six 425 kW motors fed by three 4-Quadrant converters and inverters in a 4-car configuration with the dc link 900 V.

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[2] Two induction motors are usually use. However if Permanent Magnet (PM) motors are used each motor must be fed individually by a single inverter.

The MLC unit will be ideal for integrating with a single traction package incorporating inverter and dc link filters, as shown in Figure 27. The traction inverter and flywheel controller can be identical, resulting in a much simplified and compatible design. The only additional circuitry required will be a 6-IGBT inverter that is identical to the traction inverter. In comparison super capacitor storage requires a bi-directional wide range dc-dc converter, which has considerable size and weight.

If two MLC devices are integrated with two traction packages, this will provide maximum continuous power of 1.3MW for 41 seconds. The total delivered useable energy would be 15kWh, which could power the train for nearly 700m at an average speed of 60 kph. The total additional weight of two units is 800kg and the total volume would be 0.28 m^3. Even if additional tolerances are added, this system will outperform other types of storage devices.

A typical MLC flywheel for road applications runs at lower speeds compared with the racing car version in order to last longer. The racing car version runs at higher speeds, in access of 40,000 rpm, and last for a few races or one season only. For the proposed device, higher reliability and durability will be required. This may mean running at lower speeds, the specified speed being 36,300 rpm. However, as the energy stored in a flywheel is proportional to the square of its speed, the energy specific will drop by the square of the speed ratio. Nevertheless, even if the energy specific is halved, e.g. by dropping to a maximum speed of say 25,600rpm, the performance will still be impressive. Refer to Table 10 for comparison between the MLC theoretical device and super capacitor storage.

The efficiency and operating temperature range of the MLC flywheel are better than super capacitors. The life cycle quoted is 10 times of that of a super capacitor. However, it is expected that the flywheel will require routine maintenance and probably regular overhaul for every few years of operation.

The cost of MLC flywheel, excluding development cost, is expected to be considerably lower than super capacitors, as the materials used to make the flywheel are conventional in nature and relatively inexpensive. Consequently recyclability and risk of disposing toxic materials are less of a problem.

Safety and reliability are the two main issues which need to be addressed in the design of this device.

6.4 Hydraulic Energy Storage

Section 4.2 provides a brief description of hydraulic energy storage systems. Usually, hydraulic storage systems are developed as part of a complete mechanical design of the vehicle, including all subsystems. Generally, modern rail vehicles, diesel in particular, are offered with complete and integrated systems incorporating eco-driving, turbo pack, hydraulic storage, etc. Subsystems such as hydraulic accumulators, turbo charger, transmission system, etc. are all integrated within the same vehicle. Furthermore systems are being developed to utilise the waste heat and use it back for auxiliaries.

Integration of hydraulic systems is not a simple task and must be part of the overall mechanical design of the vehicle. As such, investigation is limited to the overview and performance of these systems only.

6.5 Sustainability and Environments

Nanotechnology is the underlying technology used in Li-ion batteries and super capacitors. This technology is based on nano-structured electrode materials and nano-porous silicon and titanium dioxide for improving the performance of Li-ion batteries and super capacitors. The technology is also used in advanced photovoltaic cells.

However, at present relatively little is known about the environmental impact of nano-particles and recycling and the recovery of nano-materials. In a few cases though it is shown that chemical composition, size and shape contribute to toxicological effects, (see Ref. 173).

It is therefore important to determine the true environmental impact by assessing recyclability and compare benefits against risks based on life cycle analysis. This approach must also be applied if different types of batteries are used. See to Ref. 174 which presents an impact assessment methodology for different types of batteries.

The other problem with lithium is sources. Lithium is found in rocks and sea water. The world‟s largest reserve exists in Bolivia, in Salar de Uyuni (50% of the world‟s reserves, Ref. 166). Estimates predict that the world will need 500 kilo tonnes a year just to service a niche market, e.g. batteries for laptops, mobile phones, cameras, etc. Car batteries are far larger and for lithium battery electric cars to become the norm it would need far more lithium. Without new production, and supply stability, the price of lithium will rise prohibitively.

The case for flywheels and hydraulic accumulators is relatively less demanding as the materials used are of conventional nature, and in many cases recyclability and recovery processes are well defined and the environmental impact is well understood.

6.6 Comparing Different Energy Storage Systems

Super capacitor and battery energy storage systems are electrical devices that are almost maintenance free. However, cost is the main issue for both, and for batteries, useful life is also a problem. Super capacitor storage is suitable for discontinues electrification where supply gaps are in the order of 100s of metres. Batteries on the other hand are suitable for discrete electrification to power the train for distances of a few km. The outline designs for super capacitors and batteries described in sections 6.1 and 6.2 respectively are compared in Table 9. Three super capacitor storage sizes, Cap-A, Cap-B and Cap-C described in Table 7, are compared with two battery storage sizes, Bat-A and Bat-B, in which Bat-A is operated at two different levels of DOD to optimise range against life.

	Super Capacitor			Li-ion Battery		
	Cap-A	Cap-B	Cap-C	Bat-A		Bat-B
Total weight (ton)	4	3	1.8	6		4
Total volume m^3	8	5	3	5		3.8
Cost (thousand £)	200	120	75	300		190
The figures for weight, volume and cost are indicative including a whole system, but do not include the development cost.						
Continuous Power (MW)	1	1	1	1	1	1
Duration (sec)	30	15	9	600	300	300
Usable Energy (kWh)	8.33	4.16	2.5	166	83.3	83.3
Max stored Energy (kWh)	7.0	5.5	3.3	480		225
Min Specific Power (W/kg)	500	860	1000	250		400
Min Specific Energy (Wh/kg)	5.5	4.7	3.3	120		80
Range at 60kph speed (km)	0.5	0.25	0.15	10	5	5
Cycles @ % DOD	>1M 75%	>1M 75%	>1M 75%	>3k 35%	~10k 17.5%	>3k 42%
Useful Life (years)	~20	~20	~20	~ 3	~ 5	~2
DOD of the battery determines its useful life and therefore shorter range requires lower DOD hence longer life. Shallow cycling (35% max) has been assumed for EHV energy storage requirements. As such battery life quoted above may be conservative.						
Operating temp. C^o	-20 to +40			-20 to +40		
Efficiency %	> 90			~ 90		
High operating temperatures could be an issue for super capacitors as shorter life is expected. It is not an issue for batteries. The efficiency depends on the rate of charging and discharging as it is determined by the ESR, the higher the charging/discharging current the lower the efficiency. All figures are indicative						

Table 9 Comparison of train onboard energy storage devices. Indicative figures of a lithium ion battery storage system that can be operated at two durations of 5 or 10 minutes at full load of 1MW (Bat-A) and smaller battery (Bat-B), compared with three super capacitor storage systems Cap-A, Cap-B and Cap-C to operate at 30, 15 and 9 seconds respectively, all providing 1MW power continuously.

The super capacitor design Cap-C is compared with a theoretical MLC flywheel design in Table 10. The early indications show that the flywheel is a superior energy storage device compared with super capacitors. The issues with flywheels are safety and reliability. Both of these are currently under extensive investigation by different manufactures and developers.

	Super Capacitor (Cap-C)	Theoretical MLC flywheel
Total weight (ton)	1.8	0.8
Total volume m^3	3	0.28
Cost (thousand £)	75	considerably lower [A]
Continuous Power (MW)	1	1.3
Duration (sec)	9	41.5
Usable Energy (kWh)	2.5	15
Min Specific Power (W/kg)	1000	1625
Min Specific Energy (Wh/kg)	3.3	25
Max stored Energy (kWh)	3.3	20
Range at 60kph speed (km)	0.15	0.69
Cycles @ % DOD	>1M @ 75%	10M @ 75% [B]
Useful Life (years)	~20	~10 [B]
Maintenance	none	medium [B]
Recycling / hazardous materials	low risk	very low risk [A]
Safety	low risk	controlled [C]
Reliability	highly reliable	unknown [B]
Package	flexible	single unit
Integration	extensive ancillaries	relatively simple
Operating temp. C^o	-20 to +40	-40 to +55
Efficiency %	> 90	~ 98

[A] Materials used are conventional in nature and relatively inexpensive (e.g. the current price of carbon fibre is £25/kg compared with steel £0.7/kg).

[B] The flywheel will require routine maintenance and probably regular overhaul every few years.

[C] Extensive safety testing is being carried out.

Table 10 Comparison between a theoretical MLC flywheel and super capacitor storage

The useful lifetime of the flywheel is dependent on speed and the operating environment such as the levels of shocks and vibration. In the F1 racing car the flywheel is run at higher speeds and subjected to large magnitudes of g-forces and vibration, consequently its life is short.

A typical MLC flywheel in F1 racing cars runs at 55,000 rpm and encounters continuous vibration of 100g+, and shock loading of up to 10g. Its cycling life is around 50,000 giving approximately one year of operation (this is a long time for F1 cars). The automotive (road) version of a similar flywheel may run at lower speeds, around 40,000 rpm, and encounters considerably lower vibration and therefore it has a longer cycling life of more than 10,000,000. This may translate into 20 years operation provided that a maintenance regime is in place which may include routine and major maintenance.

An alternative design based on CTV for F1 flywheel would deliver typically 60 kW power and stores 980kJ (480 kJ usable), life 20,000 km between rebuilds (or approximately four races including preparations, testing, etc.). The following parameters are approximate; weight is around 28 kg, volume 15 litres, round trip efficiency 70%, heat rejection 3kW and speed at 65,000 rpm for typically 5 kg versions. The road version typically has power of 45 kW, storage 570 kJ (340 kJ usable), life 250,000 km / 10 years, weight 35-40 kg, volume 18-20 litres, round trip efficiency 70%, heat rejection 3kW (duty cycle dependent), speed 50,000 rpm for the 7 kg version. Generally, the control systems employ CAN networks and links.

A comparison between typical MLC and CVT flywheels for automotive (road) applications is shown in Table 11.

	CVT Flywheel	MLC Flywheel
Power (kW)	45	120
Usable Energy (kWh)	0.094 (0.34MJ)	0.579 (1.27MJ)
Weight (kg)	35	40
Useful Life [A]	250,000 km / 10 years	10M cycles / 20 years
Volume (litres)	18	17
Speed rpm	50,000	40,000
Round Trip Efficiency %	~ 70	~ 98
Integration [B]	Mechanical	Electrical

[A] Over the device"s useful life regular service will be required which could be anything between a few months to a few years intervals. These figures are not available.

[B] In a mechanically driven vehicle, such as diesel hydraulic, interfacing electrical flywheel will require additional M/G set. For vehicles with dc bus/link, such as diesel electric or electric vehicles, interfacing mechanical flywheel will require additional M/G set.

Table 11 Comparison between CVT and MLC flywheels in automotive applications

The CVT flywheel must be integrated mechanically through the CVT and as such it must be mounted close to the drive shaft. In comparison the MLC flywheel is integrated electrically and can be installed wherever suitable. The MLC technology is much more efficient and would require less maintenance. In addition, integrating the MLC electrically with the onboard traction equipments is much simpler than mechanically integrating the CVT. The cost of MLC could be lower as fewer mechanical parts are involved, and also MLC reliability could be better.

In terms of safety both devices have a potential for catastrophic failure. However there is a high degree of safety mechanisms in both. Generally, the MLC flywheel relies on the containment which has to withstand the crushing force of the composite material, which is far less than the load of discrete metallic fragments. Usually, CVT flywheels utilise the space inside the rotating part to install a static steel ring, in the event of a failure the two rings crash and dissipate the stored energy, creating effectively a „plasma‟ effect. The stator in the MLC flywheel acts in the same way.

7 Design of Hybrid Traction Systems

This section presents the trends in designing new hybrid traction systems to ensure maximum benefits are achieved in terms of high efficiency, lower losses, minimum energy consumption and meeting the traction demands of the drive system.

One of the obvious design trends to minimise energy consumption is to minimise the weight of rail vehicles. Lighter rail vehicles will also help in minimising the track damage thereby reducing the cost of maintenance.

At low speeds, below 80 kph, the energy reduction in most types of trains would be nearly proportional to the weight of the train. This is because all the forces affecting the train at low speeds are approximately proportional to the train mass. These include acceleration force, gradient force, curvatures force and the force resulting from the first two Davis coefficients (A and B) of the track and rolling resistances. However, at higher speeds the third Davis coefficient (C), which is aerodynamic dependent, becomes a dominant factor and, as such, considerable effort normally goes into designing the shape of high-speed trains.

Reducing the train weight, however, has implications on the crash worthiness. This document does not discuss these effects but will focus on the electrical designs that minimise energy consumption.

The second factor affecting energy consumption is the design of the traction drive package including the front end transformer, filters, power electronics devices such as converters and inverters and the traction motors.

The front end transformer is the heaviest component. Research in this area is focusing on using new materials that can operate at flux densities of up to 2.6 Teslas and also using power electronics converter modules to operate at high frequencies to reduce the size of the transformer. For example power-electronics‟ based transformers operates at frequencies between 2kHz to 10kHz and weigh nearly half that of a conventional transformer.

Modern Integrated Power Modules (IPM) compared with conventional IGBT have double the power rating (800 kW IPM compared to 400 kW IGBT), are lighter by 20%, smaller by 30% and cost less. Modern IPM can operate at voltages up to 6.5kV and currents up to 2.4kA.

A typical power circuit of an ac drives package is shown in Figure 26. The diagram shows a 25kV multiple interlaced front end 4-quadrant two-level converters feeding a dc link, and a number of 3-phase two-level VSIs feeding multiple induction motors. There is usually one VSI per bogie incorporating two traction motors, and a rheostat braking system connected directly to the dc link.

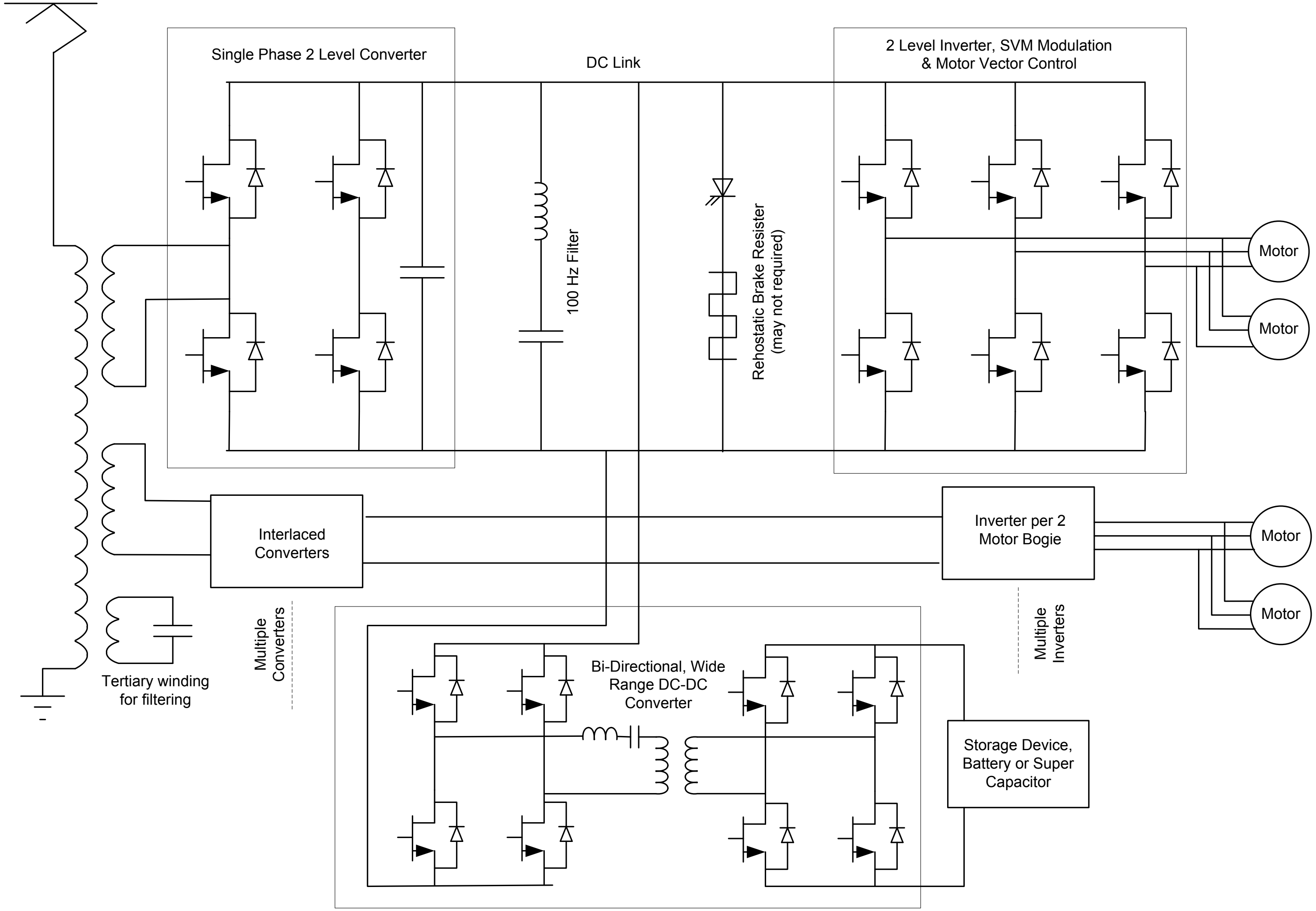
Single Phase 2 Level Converter
DC Link
2 Level Inverter, SVM Modulation & Motor Vector Control
100 Hz Filter
Rehostatic Brake Resister (may not required)
Motor
Motor
Interlaced Converters
Inverter per 2 Motor Bogie
Motor
Motor
Multiple Converters
Multiple Inverters
Tertiary winding for filtering
Bi-Directional, Wide Range DC-DC Converter
Storage Device, Battery or Super Capacitor

Figure 26 Typical power circuit of 25kV pulse converter and ac drive inverter including energy storage device controlled by a dc-dc converter

This design is typical of modern ac drive 25kV locomotives, or EMUs, that are generative braking capable. DEMUs have similar equipment, with the exception that the front end transformer and converter are replaced with a diesel alternator-rectifier set.

The dc link filters, and in particular the capacitors, are designed and rated to bypass the load current ripples and therefore have a completely different function compared with a super capacitor if used as a storage device.

Figure 26 also shows an energy storage device fed by a bi-directional wide range dc-dc converter which is connected to the dc link. The transformer used in this converter operates at high frequency and therefore its size and weight are considerably smaller than a comparable low frequency power transformer. The bi-directional and wide-range dc-dc characteristics of this converter are necessary for electrical storage devices such as batteries or super capacitors since the energy stored is in electrical form as dc.

However, for mechanical storage devices, such as MLC flywheels, the power controller can be considerably simplified. As the energy stored is in mechanical form (kinetic energy) it can be controlled using an inverter of the same characteristics as that used for the traction drives. This is shown in Figure 27. In fact, identical IGBT modules could be used for both except the operating frequencies of the flywheel are higher. This arrangement would have the advantage of utilising the filters of dc link to eliminate harmonics produced by the flywheel inverter. This helps to eliminate harmonic distortion, unlike using the flywheel on trackside for energy storage where harmonics produced by the inverter could propagate in the dc supply and cause EMC problems in signalling systems.

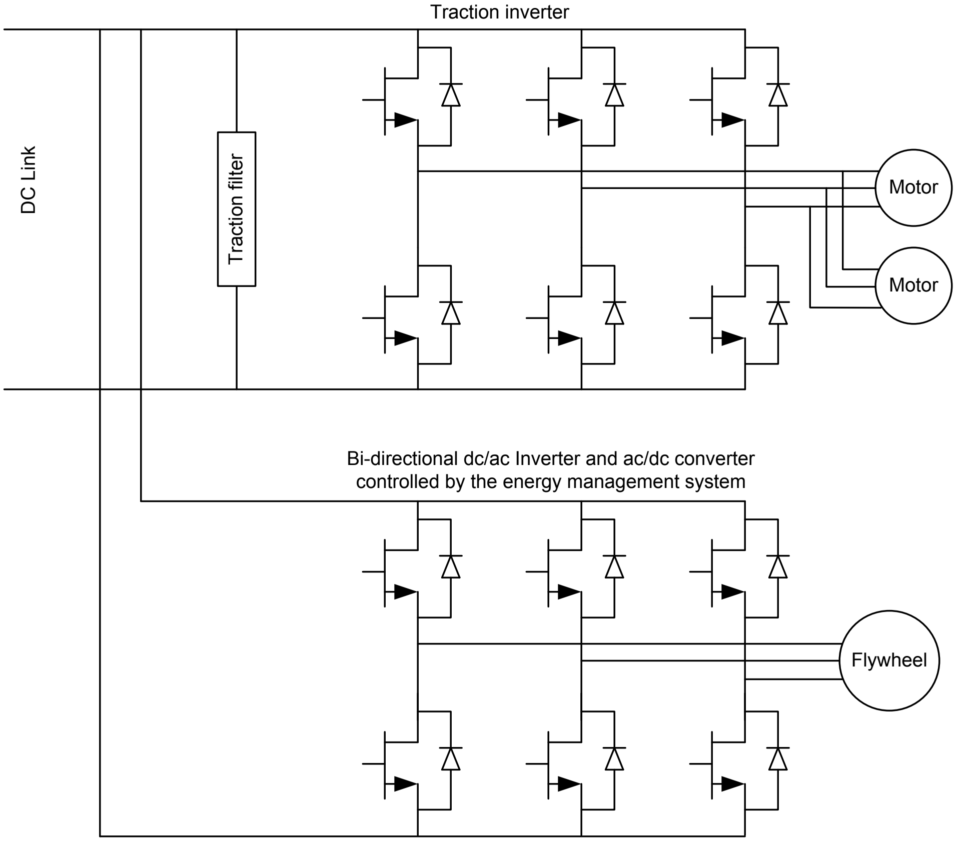
Traction inverter
DC Link
Traction filter
Motor
Motor
Bi-directional dc/ac Inverter and ac/dc converter controlled by the energy management system
Flywheel

Figure 27 Power electronics circuit interface of flywheel

The additional EMI from the flywheel inverter will not be worse than that of the main inverter. The dc-link filter must be designed to eliminate the harmonics generated by both inverters.

The system presented in Figure 26 is a typical series hybrid type usually used for high power traction where the energy storage device normally connected to the dc link. Parallel hybridisation can also be used for smaller power applications such as buses, small trams and indeed passenger cars, as shown in Figure 4. Clearly, for such applications the power circuit will be different.

The energy losses between the contact-wire to the track-wheel interface can be determined by evaluating the efficiencies of the single phase 25kV transformer, front end converters, dc link filters, inverters and traction motors. With modern power electronic controllers the drive is capable of operating anywhere within the confines of its speed-torque characteristics at different efficiencies as shown in Figure 28.

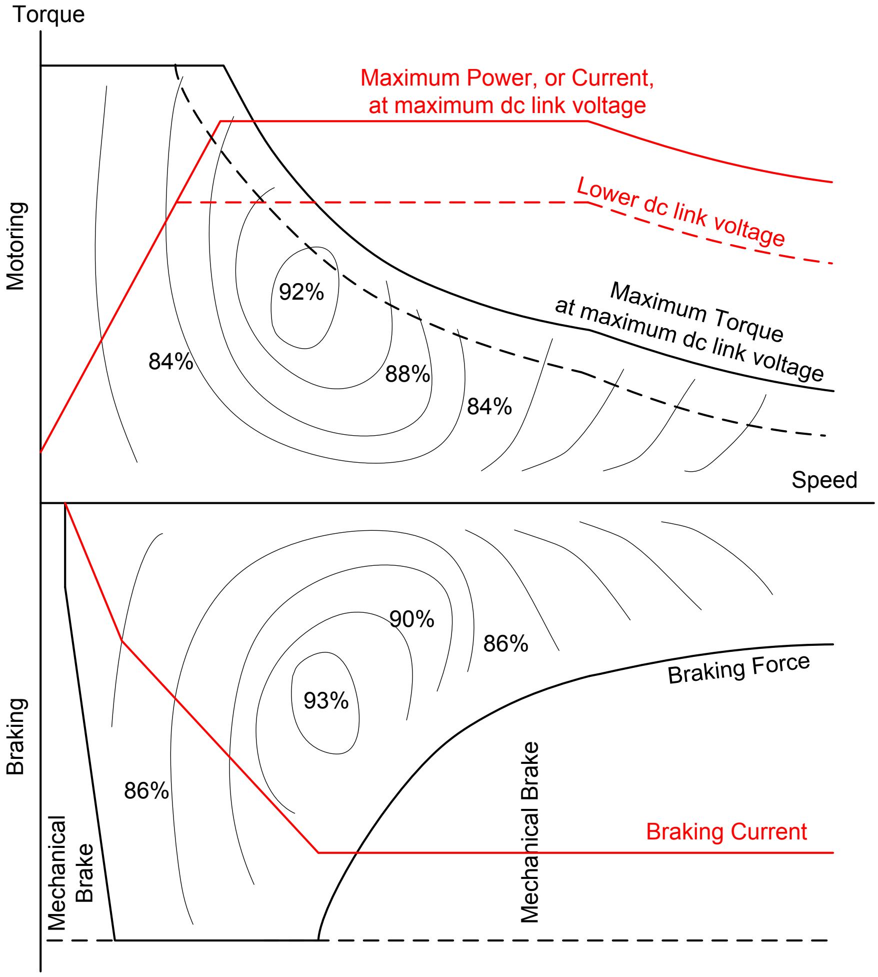

Figure 28 Efficiency maps of motoring/braking characteristics utilising the space vector modulation and vector control scheme of an ac motors traction drive

The efficiency is optimised in such a way that the overall losses are minimised at speeds where the train is usually operating. It is the limitation of the power electronics that determines the envelope of the drive capability not the motor thermal limits. The semiconductor devices have thermal time constants in m seconds, compared with the overload capability of the drive of 10s of seconds, which in reality is the steady state for power electronic devices. Therefore the operating limits shown in Figure 28 are the limits of the switching devices.

Two rating levels may be defined for the traction motor, continuous rating and overload operation rating for durations less than 30 sec. For the semiconductors, and associated cooling devices, the rating must be specified to meet the overload rating continuously.

At the introduction of a train onboard energy storage device in a series hybrid, (see Figure 26), the power electronic drive would have to tolerate a wider range of dc link voltages. To achieve this, and for there to be stable and efficient control, it is required that techniques such as Space Vector Modulation (SVM) must be introduced instead of the traditional Pulse Width Modulation (PWM). SVM has the advantage of utilising the available dc link voltage to its maximum level. It also minimises the device switching losses, and minimises the output harmonic distortion, thereby reducing harmonic losses in the motors. If implemented in real time, such as the use of Digital Signal Processing (DSP), SVM switching technique can be adapted such that it can cope with the storage-system‟ limited output.

Figure 29 presents a typical scheme for adaptable SVM switching strategy that is a function of the dc link voltage and output control frequency.

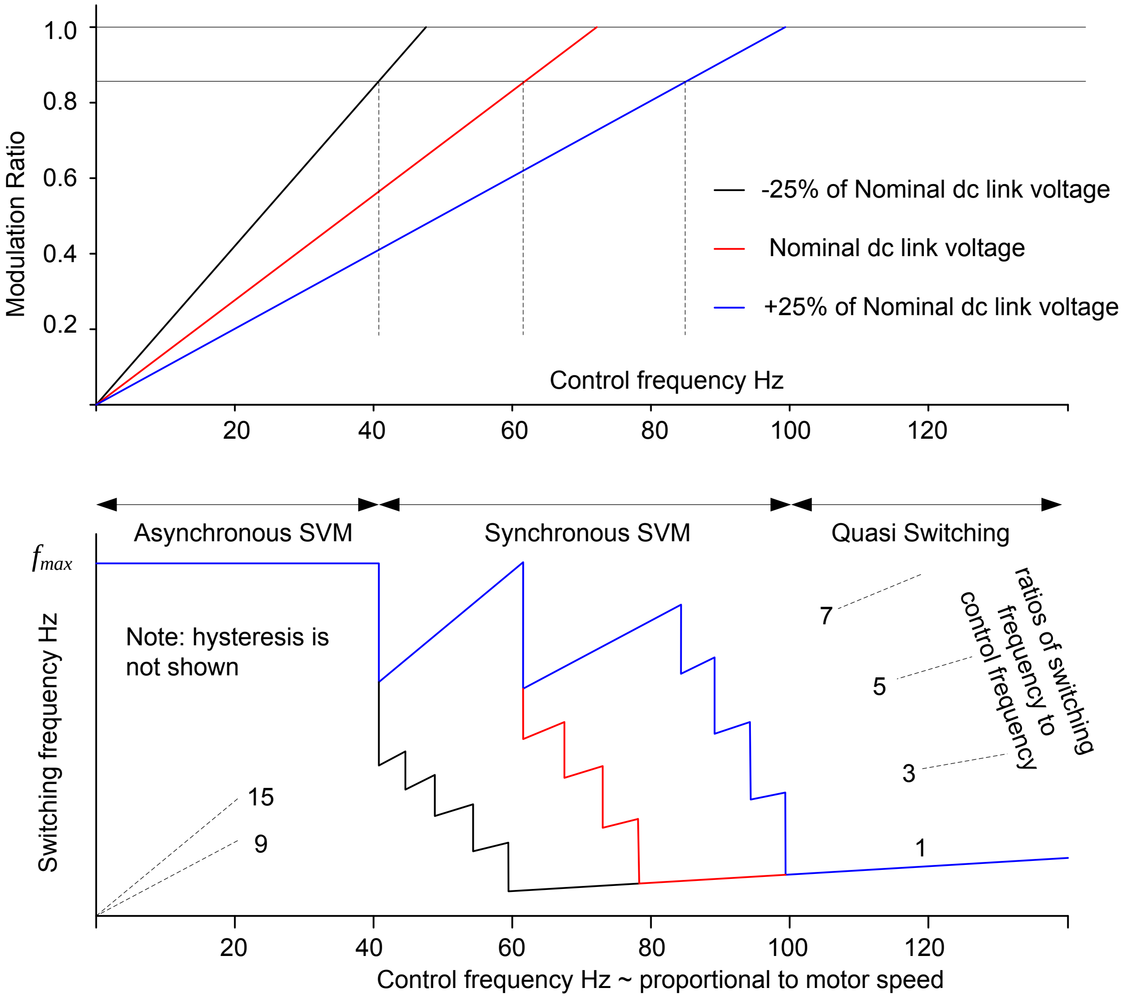

Figure 29 SVM control scheme of a variable dc link voltage suitable for hybridisation

Recently, 3-level converters and inverters are being introduced specifically for high-power applications. A simplified 3-level scheme of a 25 kV line converter and 3-level VSI is shown in Figure 30.

A 3-level inverter has the advantage of reducing the switching losses per power device to nearly half, since each device is subjected to half the dc link voltage when turned on or off. The other advantage is cleaner sinusoidal output voltage having significantly reduced switching harmonics distortion, and this reduces losses in the traction motors.

The SVM switching scheme for a 3-level inverter is shown in Figure 31. The SVM scheme of a 2-level VSI is a subset of this diagram and is represented by the inner hexagon. Vectors V1 and V2 can be constructed from either two or three principal vectors enclosing them in a triangle, for the case of 2-level and 3-level respectively.

A disadvantage of 3-level converters is the required number of switching devices which is double the equivalent of a 2-level scheme. This however can be offset by the switching losses per device, which is half, and consequently reducing the cooling requirements.

In any of the schemes mentioned above, the speed-voltage-frequency control of the traction motors is achieved using the vector control theory, which is also known as a field oriented control. This method is almost universally used for traction applications.

Also recently Permanent Magnet Motors (PMM) have been introduced, instead of conventional induction motors. PMM are more efficient and smaller in size by some 20%. PMM can achieve power specific of 1000 W/kg, which cannot be matched by any induction motor. However PMM are more expensive as rare materials are used in their construction. PMM motors are also less robust than induction motor.

There are several types of PMM including the most common Surface Permanent Magnet, Interior Permanent Magnet, Interior Permanent Magnet - Flux Squeeze and Permanent Magnet Reluctance Machine. The classification is very much dependent on the way the permanent magnet is shaped within the rotor, (see Figure 32).

The last area in energy storage and hybridisation on the railways is to set reliability and availability targets for energy storage and hybrid systems. The automotive industry has adopted a reliability metric for hybrid systems to deliver maintenance-free service for 15 years or 150,000 mile whichever comes first. Similar metric could be useful for the railway applications.

The conventional probability, of one failure in a billion hours of operation 10^9 h used for extremely remote probability failure for safety critical systems, would have to be set at a higher level for energy storage applications, probably in the order of 100s failures in 10^9 h. Hence, the acceptable figure for Mean Time Between Failures (MTBF) may be in the order of 10^9 h / 100s.

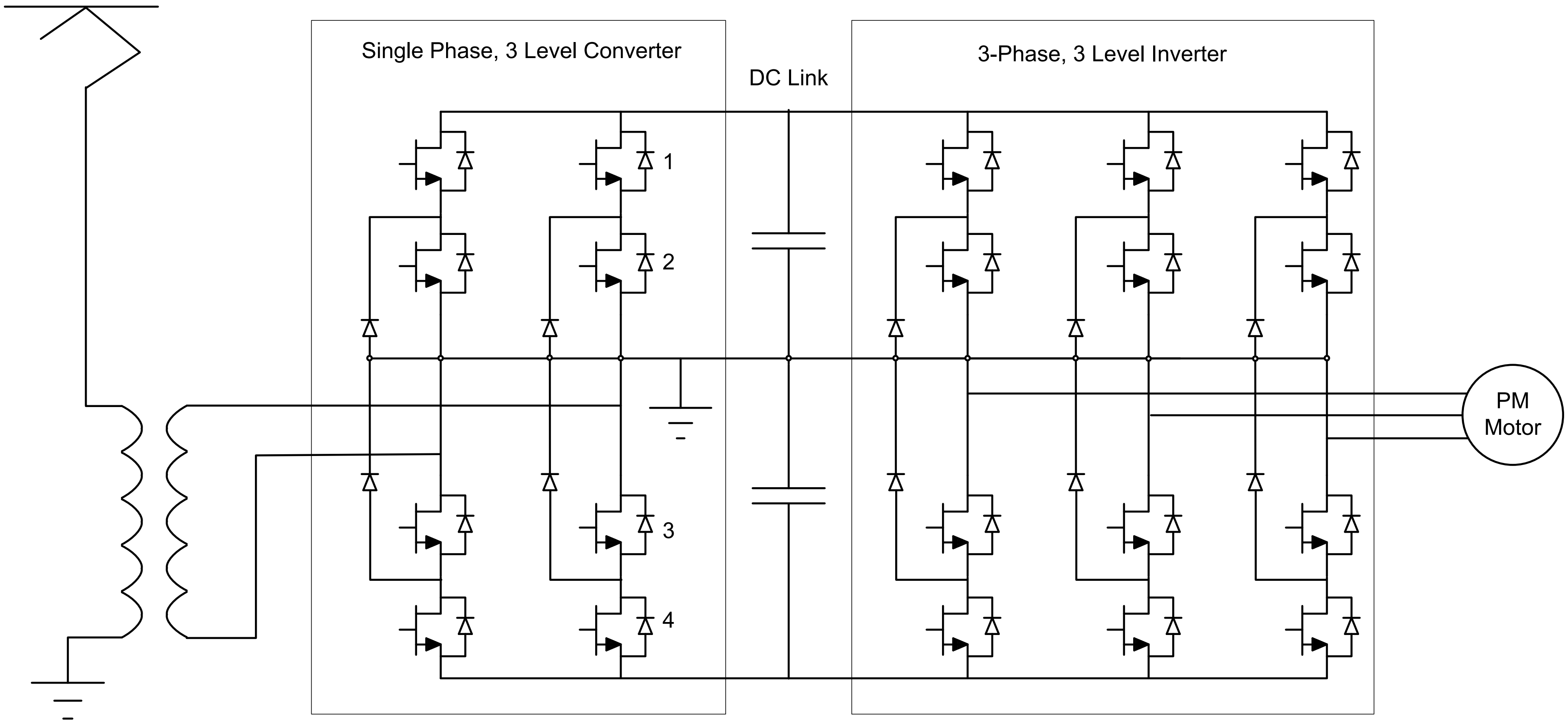

Figure 30 Power circuit of newly introduced 25kV 3-level pulse converter and ac drive inverter, one bridge is shown only

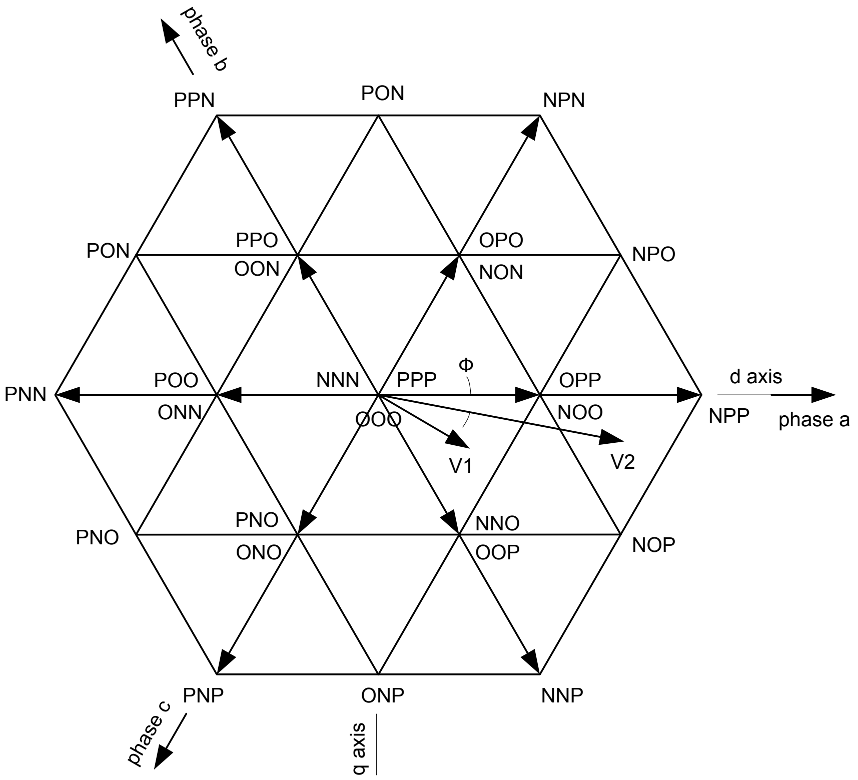

Figure 31 Space Vector Modulation SVM of 3-level inverter

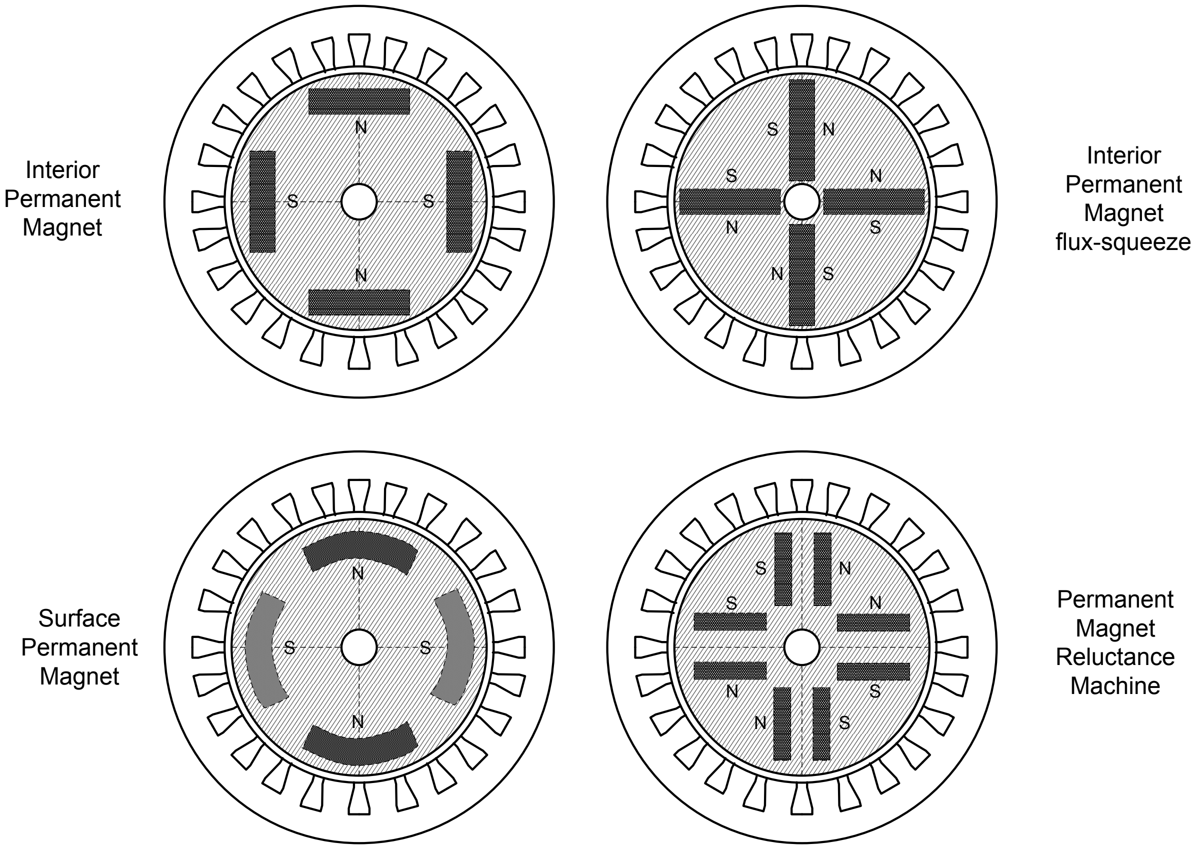

Figure 32 Different types of permanent magnet traction motors

8 Conclusions

Batteries and super capacitors have recently improved considerably. Within the next few years it is expected that performance will improve and costs will come down. This will make battery and super capacitor applications in the railway applications viable.

Batteries suffer from a limited lifetime and cost is also an issue. The useful life of a battery is a few years and could be extended to a maximum of 10 years provided the charging/discharging cycling is maintained within low limits. Batteries are suitable for „discrete" electrification schemes.

The issue with super capacitors is cost. The lifetime of super capacitors is almost the same as that of traction equipments. Super capacitors have a high specific power density but poor specific energy density compared with batteries. Super capacitors are suitable for „discontinuous" electrification schemes.

Modern MLC flywheels have superior performance compared with super capacitors in terms of weight, volume, cost and lifetime. There are two issues such as safety and reliability which are addressed extensively.

An electric train equipped with a storage device can be used for both storing braking energy and powering the train for short distances up to 500 metres. This can be implemented on both dc or ac electrified lines, though on dc storing regenerative braking energy is more of an issue compared with ac.

The above scheme could be extended to self power the train for longer distances, of up to a few km. This would require the use of batteries instead of super capacitors and would be more suitable for running dc light rail through locations such as town centres or heavily populated areas.

An on-board energy storage device would enable simplifying of the supply design. The train can be self-powered to avoid discontinuities in the supply in places such as bridges, complex junctions, tunnels, station throats, etc. The storage device would also save energy by recovering the regenerative braking energy.

Diesel hybridisation is another application of energy storage. It is reported that savings of up to 25% can be achieved when the energy management system of the train is closely integrated with the duty cycle.

Energy storage devices can also be used for trackside applications, in particular on dc to store regenerative braking energy and also for smoothing out the peak load demands.

The last application is the use of battery powered rail vehicles and battery powered railway applications. The main criteria in such applications are the operating time, range, charging time, useful life, size, cost and weight of the battery.

The merits of each application outlined in this report need further detailed assessments and possibly line specific evaluation. To establish theoretical limits for each of the applications and assess their feasibility, a system-wide theoretical simulation will be necessary.

The objective of the second phase is to develop an explicit energy model for railway systems in order to address the issues surrounding the use of energy storage devices on the railway.

Appendix A: Reference List

Keys in the Category field are as follows:

B Battery, H Hybrid, F Fuel Cell, S Super Capacitor, E Energy Storage and G General relevant work

No	Reference	Cat	Source	Comment
1	"Lithium-~Ion Batteries, Solid-Electrolyte Interphase", Perla B Balbuena, Yixuan Wang, Imperial College Press, 2004	B	Text book, British Library	Theory of Lithium Ion Batteries
2	"Lithium Batteries, Science and Technology", Gholam Abbas Nazri, Gianfranco Pistoia", Kluwer Academic Publisher, 2004	B	Text book, British Library	Theory of Lithium Ion Batteries
3	"PEM Fuel Cells, Theory and Practice", Frano Barbir, 2005	F	Text book, British Library	Theory of PEM fuel Cells
4	"Fuel Cells, Engines and Hydrogen, An Exergy Approach", Frederick J Barclay, 2006	FG	Text book, British Library	Use of Hydrogen in ICE
5	"Modern Power Electronics and AC Drives", B K Bose, Prentice Hall PTR, 2002	G	Text book, IET	Power electronics fundamentals and equipments
6	"Power Electronics Handbook: Devices, Circuits and Applications", M H Rashid, Academic Press, 2006	G	Text Book, British Library	Power electronics fundamentals and equipments
7	"Pulse Width Modulation for Power Converters, Principles and Practice", D G Holmes and T A Lipo, IEEE Press	G	Text book, IET	PWM techniques and principles
8	"Industrial Applications of Batteries: From Cars to Aerospace and Energy", M. Broussely and Gianfranco Pistoia Elsevier Science, 2007	B	Text book	Industrial batteries, types and applications
9	"Electric and Hybrid Vehicles: Design Fundamentals", Iqbal Hussain, CRC Press, 2003	H	Text book	EHV design fundamentals
10	"Handbook of Automotive Power Electronics and Motor Drives", Ali Emadi, CRC Press, 2005	HG	Text book	Power electronics drives for HEV
11	"Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals", Mehrdad Ehsani, , Sebastien E. Gary, Yimin	FH	Text book	EV, EHV and FHV fundamentals

No	Reference	Cat	Source	Comment
	Gao and Ali Emadi, CRC Press, 2004			
12	“Vehicle Propulsion Systems: Introduction to Modeling and Optimisation”, Guzzella, Antonio, Sciarretta, Springer 2007	GH	Text book	Propulsion systems of EHV
13	“Propulsion Systems for Hybrid Vehicles”, J M Miller, IEE, 2003	H	Text book	Propulsion systems of EHV and FHV
14	“Modern Electric Vehicle Technology”, C C Chan and K T Chau, Oxford University Press, 2001.	B	Text book	EV technology
15	“Development of Energy Storage System for DC Electric Rolling Stock applying Electric Double Layer Capacitor”, Sekijima, Y Kudo, M Inui, Y Monden and I A Oyama, WCRR 2006	HC	Conference paper WCRR 2006	Experimental trial of super capacitor storage on train on the Central Japan Railway company, Toshiba Corporation, Tokyo Japan
16	“Development of Fuel Cell Rubber Tired Tram (FRT)”, J K Mok, S Chang, K H Moon, J Y Lee and D H Koo, Korea Railroad Research Institute (KRRI), WCRR 2006	FH	Conference paper WCRR 2006	Fuel cell powered bus, or termed rubber tired tram, in Korea
17	“Rail-car hybrid trains to reduce fuel consumption and emissions”, R Cheli, G Grande, R Giglioli, R Manigrasso and G Pede, WCCR 2006	H	Conference paper WCRR 2006	Theoretical investigation of a hybrid rail vehicle
18	“Field tests of hybrid power supply system for dc electric railways”, T Yamanoi, S Umeda, Y Nakamura, K Kudo and J Ishii, West Japan Railway Company, WCRR 2006	HG	Conference paper WCRR 2006	Trackside application of Lithium Ion battery on dc railway for energy storage, for peak demand and regenerative braking.
19	“A hybrid locomotive for demonstration and investigation on energetics”, A Jeunesse and M Thiounn, SNCF, WCRR 2006	HG	Conference paper WCRR 2006	Experimental locomotive for energy studies by SNCF
20	“A feasibility design and evaluation of fuel cell powered train”, T Furuya, K Kondo and T Yamamoto, Railway Technical Research Centre, Japan, WCRR 2006	FH	Conference paper WCRR 2006	Feasibility design of fuel cell powered train by RTR Japan
21	“Introduction of power electronics in traction power supply fixed installations”, C. Courtios, E. Carpentier, SNCF French Railways Infrastructure‟s Engineering, France, WCRR 2008	G	Conference paper WCRR 2008	Power electronics systems application on the railways, recent developments
22	“Driver‟s behaviour improvement when High Speed Train is diverted”, C. Blatter, C. Joie, C. Weber, SNCF French Railways	G	Conference paper WCRR 2008	Optimisation of the train driving conditions under service disruptions

No	Reference	Cat	Source	Comment
	Infrastructure‟s Engineering, France, WCRR 2008			
23	"Control Strategy of Four Single Phase AC-DC Converter in Auxiliary Block for High Speed Train", Y C Kim, T H Kim, K H Jang and J Choi, Hyundai-Rotem, S Korea	G	Conference paper WCRR 2008	Front end converter design for auxiliary power supply applications
24	"Analyzing the Potential of Energy Storage on Electrified Transit Systems", M. Chymera, A.C. Renfrew, M. Barnes University of Manchester, WCRR 2008	EG	Conference paper WCRR 2008	Analysis of energy storage on the railways
25	"Innovative lightweight traction system technologies employing power electronics on the Shinkansen high-speed EMUs - Environmentally-friendly aspect and innovative traction systems" Y Hagiwara, S Ishikawa and M Furuya, Central Japan Railway, WCRR 2008	G	Conference paper WCRR 2008	General commercial paper. It contains useful design parameter
26	"Integrated simulator for AC traction power supply", T Uzuka, M Akagi and Y Hisamizu, Railway Technical Research, WCRR 2008	G	Conference paper WCRR 2008	General simulation of ac railway supplies
27	"Optimal driving strategy for traction energy saving on DC suburban railways", Y V Bocharnikov, A M Tobias, C Roberts, S Hillmansen and C J Goodman, IET Electric Power Applications, 2007	H	IET Paper	Analysis of optimum driving for energy saving
28	"The application of fuel cell technology to rail transport operations", S Hillmansen, Proc. Instn Mech. Engrs Part F, J. Rail and Rapid Transit, 2003	F	IMechE paper	Fuel cell application in railways
29	"Analysis of Energy Storage Devices in Hybrid Railway Vehicles", S Lu, D H Meegahawatte, S Guo, S Hillmansen, C Roberts, and C J Goodman, University of Birmingham, 2007	H	Journal paper	Analysis of hybrid systems
30	"Chemical battery storage devices for hybrid railway vehicles", S Hillmansen, C Roberts, D Aguirre, S Singainy and C Goodman, Third International Conference on Railway Traction Systems), Japan, 2007	G	Conference paper	Batteries for hybrid applications

No	Reference	Cat	Source	Comment
31	“Final Report: Concept Validation for Hybrid Trains“, University of Birmingham, Research funded by DfT, 2008,	G	Report	Validation of hybrid trains concept
32	“A Kinetic Energy Storage System for Railways Applications”, I J Iglesias. J C Martinez, C Tobajas, M Lafoz, L García-Tabarés and C. V Coauthors, ADIF and Environment and Technology Research, Spain, WCRR 2008	EG	Conference paper WCRR 2008	Analysis of energy storage devices on the railway
33	“Energy efficiency and fuel consumption of fuel cells powered test railway vehicle”, K.Ogawa, T.Yamamoto, T.Yoneyama Railway Technical Research, WCRR 2008-06-23	F	Conference paper WCRR 2008	Experimental fuel cell light train, including general control strategies
34	“Energy efficient solutions for the complete railway system”, M Meinert, I K Rechenberg, G Hein and A Schmieder, Siemens AG, Erlangen, Germany, WCRR 2008	E	Conference paper WCRR 2008	Review and application of energy storage devices on the railway
35	“Hybrid shunter locomotive”, H Girard, J Oostra and J Neubauer Alstom Transport, WCRR 20078	F	Conference paper WCRR 2008	Fuel cell powered shunting engine
36	“The development of low floor battery-driven LRV SWIMO”, S Akiyama, K Tsutsumi and S Matsuki, Kawasaki Heavy Industries, Japan, WCRR2008	BH	Conference paper WCRR 2008	Electric hybrid vehicle operating from overhead and self powered by battery
37	“Zero-Emission, Hydrogen-Fuelcell Locomotive for Urban Rail”, A R Miller, K S Hess, D L Barnes and T L Erickson, Vehicle Projects LLC, Denver, USA, WCRR2008	F	Conference paper WCRR 2008	Fuel cell powered locomotive
38	“Development of Motor-Assisted Hybrid Traction System”, H Ihara, H Kakinuma, I Sato, T Inba, K Anada, M Morimoto, T Oda, S Kobayashi, T Ono and R Karasawa, Hokkaido Railway Company, Japan, Hitachi Nico Transmission, Japan, WCRR 2008	H	Conference paper WCRR 2008	Parallel hybrid diesel-battery for a railway application
39	“Innovative Integrated Energy Efficiency Solutions for Railway Rolling Stock, Infrastructure and Operation”, U Henning, M Bergendorff, C Spalvieri, L Nicod, C Struve, G Giannini, R Nolte WCRR 2008	E	Conference paper WCRR 2008	Application of energy efficient techniques and storage devices on the railway

No	Reference	Cat	Source	Comment
40	"Energy Storage System with UltraCaps on Board of Railway Vehicles", M Fröhlich, M Klohr, S Pagiela, Bombardier Transportation and Fachhochschule, Amberg, Germany	SH	Conference paper WCRR 2008	Train onboard application super capacitor for energy storage
41	"PLATHEE, A Platform for Energy Efficiency and Environmentally Friendly Hybrid Trains", M Thiounn, A Jeunesse, SNCF, France	EG	Conference paper WCRR 2008	Experimental locomotive for energy studies by SNCF
42	"Energy Efficient Driving Strategies for Commuter Trains – Project PEFIS", J Zajicek, A Schöbel, M Turk, Arsenal research and Technical University, Austria	EG	Conference paper WCRR 2008	Energy efficient driving strategies
43	"Theory of Ragon Plots", T Christian and M W Carlen, Journal of Power Sources, 2000	BC	Journal of Power Sources, 2000	Characterisation of energy storage devices
44	"A General Approach to Energy Optimisation of Hybrid-Electric Vehicles", M Ceraolo, A. di Donato and G. Franceschi	H	Journal paper	Hybrid vehicle analysis, general approach
45	"Microcycle-based Efficiency of Hybrid Vehicle Batteries", M Ceraolo, A. Di Donato and C Miulli, University of Pisa – Dipartimento di Sistemi elettrici e Automazione, Italy	B	Journal paper	Battery test for HEV application
46	"Modeling and Simulation of Hybrid drive trains with a friendly Man Machine Interface", M Ceraolo, A di Donato, University of Pisa - Dipartimento di Sistemi elettrici e Automazione, Italy	H	Journal paper	Hybrid vehicle man machine interface
47	"Energy storage devices in hybrid railway vehicles: a kinematic analysis", S Hillmansen and C Roberts, IMechE, University of Birmingham	H	Journal paper	Analysis of energy storage in hybrid vehicles
48	"Energy simulation of hybrid inter-city trains", Q Wen, S Kingsley and R A Smith,, Energy, Imperial College	H	Journal paper	Simulation of hybrid railway inter-city train
49	"Predictive Energy Management Strategies for Hybrid Vehicles", M Salman, M F Chang and J S Chen, IEEE VPPC Conference 2005	HG	IEEE conference paper	Mathematical modelling of energy management for hybrid vehicles
50	"Hybrid technology for the rail industry", F W Donnelly, R L Cousineau and R N M Horsley, IEEE Joint Rail Conference,	H	IEEE conference paper	High level rail application of hybrid vehicles

No	Reference	Cat	Source	Comment
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51	"Green ave Green The Green Goat Hybrid Locomotive", R Bradley Queen	H	RailPower web site	Green Goat technical paper
52	"Energy Management Strategies for a Hybrid Electric Vehicles", X He and T Maxwell, IEEE VPPC Conference 2005	H	IEEE conference paper	Fuzzy logic applied to hybrid vehicles control strategies
53	"The Optimal Driving Strategies of Electric Multiple Unit", C T Kim, D H Kim and G H Kang, National University of Technology, Korea, Poster WCRR 2006	E	WCRR 2006	Optimal driving strategies
54	"Energy for Transport", R A Smith, 25th, Thomas Hawksley Lecture, IMechE 2007	G	IMechE	Lecture on transport energy
55	"Ultracapacitor-based energy management strategies for eCVT hybrid vehicles", J Auer and J Miller, Maxwell Technologies, Switzerland, IET Automotive Electronics, 2007 3rd IET Conference	C	IET conference paper	Super-capacitor as energy storage component in automotive applications
56	"Design and Modelling of Asynchronous Traction Drives Fed by Limited Power Source", R Manigrasso and F L Mapelli, Italy, VPPC 2005 IEEE conference	EG	VPPC IEEE conference 2005	Design of IM drive under limited supply capability
57	"Integrated, Feed-Forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies", C C Lin, Z Filipi, Y Wang, L Louca, H Peng, D Assanis and J Stein, University of Michigan, Society of Automotive Engineers, 2001	EH	Journal paper, available online	Modelling of EHV in Matlab/Simulink
58	"Diagnostic Characterization of High-Power Lithium-Ion Batteries for Use in Hybrid Electric Vehicles", X Zhang, N Ross, R Kostecki, F Kong, S Sloop and B Kerr, University of California,	B	Note paper, available online	Lithium Ion battery in EHV
59	"Vehicle Simulation Results for Plug-in HEV Battery Requirements", P Sharer, A Rousseau, ~P Nelson and S Pagerit, Argonne National Lab,	BH	Note paper, available online	Simulation of battery for HEV applications
60	"Development of a "New Energy Train – hybrid type"", O Mitsuyuki, T Shinji, F Takehito, T Takashi and S Motomi, East	HF	Journal paper, available online	Hybrid vehicle development by EJR that can be adapted for fuel cell operation

No	Reference	Cat	Source	Comment
	Japan Railway Company, Journal L1577A			
61	"Bi-Directional DC/DC Converters for Plug-in Hybrid Electric Vehicle (PHEV) Applications", S Han and D Divan, Georgia Institute of Technology, USA, Applied Power Electronics Conference and Exposition, 2008. APEC 2008	G	IEEE APEC conference 2008	Bi-directional dc-dc converter application for charging and discharging
62	"Hybrid vehicle simulation for a turbogenerator based power-train", C Leontopoulos, M R Etemad, K R Pullen and M U Lamperth, IMechE 1998	GH	IMechE paper	Development of hybrid engine
63	"Flywheels for Traction Power", J Glover, application of URENCO flywheels on the Central line, LUL. MR journal, 2001	G	LUL, MR	Flywheel experiments on the Central line, LUL
64	"Flywheel Systems for Mobile Transport Applications", Ian Foley, Rev 1.2, 30 January 2009	E	Internal report	Feasibility design of flywheel by William"s Hybrid Power WHP
65	"Principle, design and experimental validation of a flywheel-battery hybrid source for heavy-duty electric vehicles", O Briat, J M Vinassa, W Lajnef, S Azzopardi and E Woirgard, IET Electric Power Applications, 2007	H	IET Proceedings paper	Design and experiment of a battery in hybrid vehicle
66	"Energy Management Strategies for a Parallel Hybrid Electric Powertrain: Fuel Economy Optimisation with drivability Requirements", E Cacciatori, N D Vaughan and J Marco, Cranfield University, IET Hybrid Vehicle Conference 2006	H	IET Hybrid Vehicle Conference 2006	Design optimisation of EHV
67	"Concept for system design for a ZEBRA battery-intermediate temperature solid oxide fuel cell hybrid vehicle", D J L Brett, P Aguiar, N P Brandon, R N Bull, R C Galloway, G W Hayes, K Lillie, C Mellors, C Smith and A R Tilly, Journal of Power Sources, 157, 2006	FH	Journal paper	Use of Sodium Nickel Chloride battery in a fuel cell vehicle
68	Pool, A, "Manufacturing Sports Cars, Mean and Green", E&T Journal, volume 3, issue 13, 2008 (Institution of Engineering and Technlogy, Stevenage)	B	IET Engineering and Technology	Latest development in Lithium Ion batteries http://www.teslamotors.com/
69	Email from Richard Neil [Richard.Neil@angeltrains.com]	G	Richard Neil of angeltrains	Diesel engine power versus speed

No	Reference	Cat	Source	Comment
	regarding the size of diesel engine, 25 July 2008			
70	"Battery Options for Hybrid Electric vehicles", G May, IET Hybrid Vehicle Conference 2006	B	IET Hybrid Vehicle Conference 2006	Choice of battery for EHV
71	"Electric and Electric Hybrid Vehicle Technology : A Survey", G Maggetto and V Mierlo, University of Brussels, IEE Seminar, 2000	H	Seminar paper	Survey of EV and EHV 2000
72	"Energy-Management System for a Hybrid Electric Vehicle, Using Ultracapacitor and Neural Networks", J Moreno, M E Orttuzar and J W Dixon, IEEE Transaction on Industrial Electronics, 2006	HC	IEEE transaction paper	Neural networks and super capacitor application in hybrid vehicle
73	"Energy Conversion and Optimal Energy Management in Diesel-Electric Drivetrains of Hybrid-Electric Vehicles", SE Lyshevski, Purdue University, Energy Conversion & Management, 2000	H	Journal paper	Optimum energy conversion in HV
74	"The SA^{2}VE(Advanced Kinetic Storage Energy System)", Dr Eng Ignacio Jorge Iglesias	HG	Railenrgy III	Trials of static flywheels project on the Spanish railways.
75	"A Gatekeeper Energy Management Strategy for ECVT Hybrid Vehicle Propulsion Utilising Ultracapacitor", J Auer, G Sartorelli and J Miller, IET Hybrid Vehicle Conference 2006	BC	IET Hybrid Vehicle Conference 2006	Super capacitor and battery combination in EHV
76	"Implementation of a modular power and energy management structure for battery-ultracapacitor powered electric vehicles", L C Rosario and P C K Luk, Cranfield University, IET Hybrid Vehicle Conference 2006	HB	IET conference paper	Structured approach to the management of EV and HEV
77	"Regenerative braking control system improvement for parallel hybrid electric vehicle", D Peng, J Zhang and C Yin, International Technology and Innovation Conference 2007	H	International Technology and Innovation Conference 2007 paper	Control management of regenerative braking energy in HV
78	"Grid power quality improvement using grid-coupled Electric Vehicle", S De Breuker, P Jacqmaer, K De Brbandere, J Driesen and R Belmans, Belgium, IET Power Electronics, Machine and Drives PEMD conference 2006	GH	IET PEMD conference 2006 paper	Hybridisation using batteries and super capacitors of electric vehicles operating from the grid

No	Reference	Cat	Source	Comment
79	"Power transfer in hybrid electric vehicles with multiple energy storage units", H C Lovatt and J B Dunlop, CSIRO Australia, IET PEMD conference 2002	H	IET PEMD conference 2002 paper	Hybrid vehicle using batteries and super capacitors
80	"A review of methods to measure and calculate train resistances", B P Rochard and F Schmid, IMechE 2000	G	IMechE proceeding paper	Methods to determine the train/track rolling and aerodynamic resistance
81	"Configuration and verification of the supercapacitor based energy storage as peak power unit in hybrid electric vehicles", Y C Joeri, V M Lataire P, Lieb M, Verhaeven E and Knorr R, Brussels University, Power Electronics and Applications 2007 European Conference	HC	Power Electronics and Applications 2007 European Conference	Super capacitor for energy storage in hybrid vehicles
82	"Improving the Efficiency of Traction Energy Use", R&D T618, Rail Safety and Standards Board (RSSB), June 2007	G	RSSB Report	Energy efficiency of traction systems
83	"Electrical energy storage systems – a mission to the USA", Global Watch Mission Report, dti, December 2006	G	dti Report	Energy storage systems
84	"A new control strategy for hybrid electric vehicles", A Soltis, X Chen, University of Windsor, Proceedings of the American Control Conference, IEEE 2003	H	Proceedings of the American Control Conference, IEEE 2003 paper	Control and management of electric hybrid vehicles
85	"An approach to achieve ride-through of an adjustable-speed drive with flyback converter modules powered by super capacitors", J L Duran-Gomez, P N Enjeti and A von Jouanne, IEEE transactions on Industry Applications, 2002	H	IEEE transactions on Industry Applications, 2002 paper	Super capacitor in hybrid electric vehicle applications
86	"Development of High Performance AC Drive Train", S Pathak and R Prakash, REVA Electric Car Company, Electric and Hybrid Vehicles, 2006, ICEHV IEEE conference	B	ICEHV IEEE 2006 conference paper	Development of high performance electric car
87	"Dynamic Lithium-Ion Battery Model for System Simulation", L Gao, S Liu and R A Dougal, IEEE Transaction on Components and Packaging 2002	B	IEEE Transaction on Components and Packaging 2002 paper	A validated numerical model of a Lithium-Ion battery
88	"Learning Energy Management Strategy for Hybrid Electric	H	Vehicle Power and	Energy management of HEV systems

No	Reference	Cat	Source	Comment
	Vehicles“,J S Chen, M Salman, Vehicle Power and Propulsion, 2005, IEEE Conference		Propulsion, 2005, IEEE Conference paper	
89	“Lithium Ion Battery Automotive Applications and Requirements”, T J Miller, Battery Conference Applications and Advances, 2002, The Seventeenth Annual	BH	Battery Applications and Advances 2002 conference paper	Review of Lithium-Ion battery applications in hybrid vehicles, 2002
90	“Performance of the Inverter with the Super Capacitor for Vector Controlled Induction Motor Drives”, K Yamashita, T Tomida and K Matsuse, Meiji University, Japan, IEEE Industrial Electronics, ICON 2006, 32nd Annual Conference	CG	IEEE Industrial Electronics, ICON conference 2006	Application of super capacitor in conventional vector control of induction motor
91	“Ultracapacitors modeling improvement using an experimental characterization based on step and frequency responses”, Lajnef W, Vinassa J M, Azzopardi S, Briat O, Woirgard E, Zardini C, Aucouturier J L, Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual	C	IEEE Power Electronics Specialists Conference, 2004	Super capacitor modelling
92	“Pilot project for efficient recovery of energy braking for DC systems”, Daniel Cornic, Alstom Transport, 3rd Railenergy workshop.	G	3rd Railenergy workshop	Trials of VCR/inverter substation on La Rochelle LRT test track
93	“Improvement of energy balance of DC power systems: Example of 2x1,5kV”, Romain Lanselle, SNCF - Direction de l'Ingénierie	G	3rd Railenergy workshop	Feasibility of an equivalent AT dc system
94	Email from Bernard Guieu of Alstom transportation on 3 February 2009 following Railenergy III meeting	C	Email	Super capacitor on Paris Metro
95	“The Affect of Battery Pack Technology and Size Choices on Hybrid Electric Vehicle Performance and Fuel Economy”, Balch R C, Burke A and Frank A A, Applications and Advances, 2001, The Sixteenth Annual Battery Conference	BH	Applications and Advances, 2001, conference paper	Investigates the effect of battery size on HEV range and fuel economy
96	“Development of a Hybrid Electric Vehicle With a Hydrogen-Fueled IC Engine“,X He, T Maxwell, and M E. Parten, IEEE Transaction on Vehicular Technology, 2006	G	IEEE Transaction on Vehicular Technology, 2006 paper	Hybrid electric vehicle with hydrogen IC engine
97	“Pulses Plus Battery System for High Energy High Power	B	Tadiran Batteries 2000,	Testing and characterisation of Lithium Ion

No	Reference	Cat	Source	Comment
	Applications”, H Yamin, E Elster and M Shlepakov, Tadiran Batteries 2000		available online	cell batteries
98	“Advanced Battery Management and Technology Project”, Vermont Electric Vehicle Demonstration Project, 1999	B	Report available online	Summary report on vehicles batteries
99	“Battery Modeling, an excerpt from the HEVsim Technical Manual”	B	Report available online	Battery modelling
100	“Advanced Lithium Ion Technology for PHEV & HEV Applications” Presentation 2007	B	Presentation available online	Available range of batteries
101	“Saft‟s „Intensium Flex‟ system makes lithium-ion battery technology easy to use for industrial applications”, SAFT Press Release 2005	B	Report available online	High level specifications of Lithium Ion batteries available
102	“P1.2 - Hybrid Electric Vehicle and Lithium Polymer NEV Testing”, J E Francfort, Advanced Vehicle Testing Activity, INL/CON-2005	B	Report available online	Report on Lithium Ion batteries used on HEV 2005
103	“Integrating advanced, lithium-based batteries into vehicles“, OAAT Accomplishment 2001	B	Report available online	Lithium Ion Battery application in HEV
104	“High-power and High-energy Lithium Secondary Batteries for Electric Vehicles”, J Arai, Y Muranaka and M Koseki, Hitachi Group Review, 2004	B	Report available online	Applications of Hitachi Lithium Ion Batteries
105	“Low Cost Li-Ion Technology”, Presentation by R Neat, ITI Energy	B	Presentation available online	Lithium Ion Technology presented
106	“Numerical Analysis on Charge Characteristics in Lithium Ion Batteries by Multiphase Fluids Model”, S Kawano and F Nishimura, JSME International Journal 2005	B	Journal paper	A model of Lithium Ion battery
107	“Numerical Simulation of Intercalation-Induced Stress in Li-Ion Battery Electrode Particles”, X Zhang,W Shyy and A Marie Sastrya, Journal of The Electrochemical Society 2007	B	Journal paper	A model of Lithium Ion battery
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109	“Ultracapacitors Provide Cost and Energy Savings for Public Transportation Applications”, B Maher, Maxwell Technologies, marketing report 2006	C	Article available online	Super capacitor applications in transportation
110	“Gateway to a New Thinking in Energy Management – Ultracapacitors”, Presentation by Maxwell Technologies	C	Presentation available online	Super capacitor characteristics and applications
111	“Power-Electronic Interface for a Supercapacitor-Based Energy-Storage Substation in DC-Transportation Networks”, A Rufer, Laboratoire d‟Electronique Industrielle, 2003	C	Presentation available online	Control system for a super capacitor
112	“Battery Solutions - Energy vs. Power”, J McDowall, Presentation by SAFT	B	Presentation available online	Lithium Ion battery presentation
113	“Ultracapacitors for Electric and Hybrid Vehicles - Performance Requirements, Status of the Technology, and R&D Needs”, Report by The Swedish National Board for Industrial Development 1995	C	Report available online	General recommendations for R&D on super capacitors
114	“Thermal Characterization of Selected EV and HEV Batteries”, Annual Battery Conference 2001	B	Presentation available online	Performance of batteries in EV and HEV
115	“Status and Prospects of Battery Technology for Hybrid Electric Vehicles, Including Plug-in Hybrid Electric Vehicles “,Briefing to the U.S. Senate Committee on Energy and Natural Resources 2007	B	Report available online	Status of the battery market for EV and HEV in 2007
116	“Sizing Ultracapacitors For Hybrid Electric Vehicles”, H Douglas, P Pillay	C	online	Sizing of super capacitor
117	“Can Ultracapacitors Provide the Power that other Storage Devices Can‟t ?”, A Schneuwly, IEE Power Engineer, March 2005	C	IEE Power Engineering magazine	Article on super capacitors
118	“Energy Storage in Advanced Vehicle Systems”, A Burke, University of California, Presentation 2005	BC	Presentation available online	Review of super capacitors and battery technologies for HEV

No	Reference	Cat	Source	Comment
119	http://web.mit.edu/2.972/www/reports/hybrid_vehicle/hybrid_electric_vehicles.html H, link to a website, tutorial on hybrid electric vehicle design and operation			Article on a website
120	http://www.energy.ca.gov/links/afv.php?pagetype=afv	E	link to a website	The web directory of alternative fuels and advanced vehicles, USA
121	http://en.wikipedia.org/wiki/Tramway_de_Nice	B	link to a website	Nice tramway
122	http://www.transportation.anl.gov/	EH	link to a website	Hybrid vehicle simulator SPAT
123	http://gcep.stanford.edu/events/workshops_transportation_10_05.html		link to a website	Global Climate and Energy Project
124	http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/12_Sadoway_10_12_trans.pdf			GCEP presentation on heavy duty batteries
125	http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/14_Burke_10_12_trans.pdf			GCEP presentation on heavy duty batteries
126	http://www.tadiranbatteries.de/eng/articles/	B	link to a website	Tadiran Batteries, Lithium Ion Batteries
127	http://www.automotivedesignline.com/howto/185301268;jsessionid=QONWA3K1SJPXMQSNDBOCKH0CJUMEKJVN C, link to a website on super capacitor characteristics and applications			
128	http://powerelectronics.com/mag/power_ultracapacitor_technology_powers/ C,			super capacitor applications in electronic circuits
129	http://www.mpoweruk.com/performance.htm	B	link to a website	Battery performance characteristics and test
130	http://www.mpoweruk.com/	B	link to a website	General information on batteries
131	http://www.thermoanalytics.com/support/publications/batterytypesdoc.html B, link to a website			Battery types and characteristics
132	http://www.railpower.com/products_hl_ggseries.html	H	link to a website	RailPower website, Green Goat manufacturer
133	http://en.wikipedia.org/wiki/Lithium-polymer	B	link to a website	Lithium-ion polymer battery characteristics
134	http://www.ulev-tap.org/	H	link to a website	European Ultra Low Emission Vehicle – Transport Advanced Propulsion
135	http://www.nesscap.com/companyinfo_article_papers.htm	BC	link to a website	Collection of technical papers on batteries and super capacitors
136	http://www.advancedautobat.com/index.html	BC	link to a website	Advanced automotive batteries

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137	http://www.iee.org/oncomms/pn/railway/06innovation_cooper.pdf	H	Web	Hitachi Hybrid Traction System
138	http://www.electronicsweekly.com/Articles/2007/11/23/42680/lithium-ion-batteries-allow-designers-to-trade-energy-capacity-and-power.htm B, Lithium Ion Batteries			
139	http://www.railway-technology.com/contractors/diesel/voith/press58.html	G	link to a website	Report railway-technolgy.com
140	http://www.parrypeoplemovers.com/	G	link to a website	Parry People Movers web site
141	Maxima – First Voith Locomotive | Innovations: EcoPack | Series	G	link to a website	Presentation by Voith
142	http://www.voithturbo.com/hydraulic_products_system_technology_accumulator-charging-units.htm	G	link to a website	Hydraulic accumulators by Voith
143	http://www.hybridcenter.org/hybrid-timeline.html	H	link to a website	Hybrid car
144	http://www.hybridcenter.org/hybrid-center-how-hybrid-cars-work-under-the-hood-2.html	H	link to a website	Hybrid car
145	www.bahnindustrie.info/uploads/media/06_voith.pdf	G	link to a website	Presentation by Voith
146	http://www.buchmann.ca/Article5-page1.asp	B	link to a website	Lithium ion batteries
147	http://www.dolcera.com/wiki/index.php?title=Hybrid_Electric_Vehicle_Battery_System			H, Hybrid vehicles design and dimensioning
148	http://www.maxwell.com/ultracapacitors/index.asp	C	link to a website	Link to Maxwell Technologies, super capacitors manufacturer
149	http://mtrl1.me.psu.edu/Simulation/Description.htm#CodeDev	B	link to a website	Online battery simulators
150	http://www.mpoweruk.com/history.htm	B	link to a website	History of battery development
151	http://www.nrel.gov/	G	Official website for NREL	National Energy Renewable Laboratory, general information
152	http://www.appliancedesign.com/CDA/Articles/Feature_Article/BNP_GUID_9-5-2006_A_10000000000000061728 C, Article on super capacitors			
153	http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html	H	Official website for PSAT	Transportation Technology R&D Centre
154	http://www.altairnano.com/profiles/investor/fullpage.asp?f=1&BzI	B	Official website for	Nano Titane batteries

No	Reference	Cat	Source	Comment
	D=546&to=cp&Nav=0&LangID=1&s=236&ID=9294		AltairNano	
155	http://www.nrel.gov/vehiclesandfuels/energystorage/model_simulation.html	H	Official website for ADVISOR	National Renewable Energy Laboratory's
156	http://www.samsungsdi.com/contents/en/product/hev/hev.html	H	From Samsung website	Article on HEV
157	http://www.batteryuniversity.com/partone-5A.htm and http://www.batteryuniversity.com/index.htm	B	BatteryUniversity.com website	Article on Lithium ion batteries and the official website of BatteryUniversity.com
158	http://www.business.com/directory/electronics_and_semiconductors/electronic_components/electronic_component_suppliers/capacitors/ultracapacitors/ C, Search for super capacitor suppliers			
159	http://www.globalspec.com/industrial-directory/ultracapacitors	BC	Search website	Useful search engine for super capacitors and batteries
160	http://webscripts.softpedia.com/script/Scientific-Engineering-Ruby/Automotive/Hybrid-Electric-Vehicle-Webinar-31510.html H, Free software for HEV design and analysis			
161	http://www.mathworks.com/industries/auto/maab.html	H	Mathworks website	Matlab / Simulink Advisory Board
162	http://www.ulev-tap.org/	H	Website of ULEV	ULEV project
163	http://www.railwaygazette.com/ur_single/article/2006/07/4432/ultracaps_win_out_in_energy_storage-1.html Super capacitor application on the railway, railwaygazette July 2006.			
164	http://www.bombardier.com/en/transportation/sustainability/technology	H	Bombardier website	MITRAC super capacitor system
165	http://pubs.its.ucdavis.edu/publication_detail.php?id=717	G	Website of ITS	Institution of Transportation Studies
166	http://news.bbc.co.uk/2/hi/business/7707847.stm	B	Website	Lithium reserves
167	“Multi-objective Optimisation of a Hybrid Electric Vehicle: Drive Train and Driving Strategy”, R Cook, A Molina-Cristobal, G Parks, C O Correa and P J Clarkson,	GH	Available from SpringerLink	Text Book
168	“High-energy, high-power Pulses Plus™ battery for long-term applications”, C Menachem and H Yamin, Journal of Power Sources 2004	B	Available from ScienceDirect	Paper on Pulses Plus batteries

No	Reference	Cat	Source	Comment
169	“Hybrid Electrical Vehicles : From Optimisation Toward Real-Time Control Strategies”, G Rousseau, D Sinoquet and P Rouchon	H	Available online	Development of HEV
170	“Optimal control of fuel economy in parallel hybrid electric vehicles”, J Pu and C Yin, Proceedings of IMechE, Journal of Automotive Engineering 2007	H	Available from the Professional Engineering Publishing	Control system fro HEV
171	“High-power batteries for use in hybrid vehicles”, Fellner C and Newman J, Journal of Power Sources, February 2000	BH	Available from IngentaConnect	Batteries for HEV
172	http://www.sae.org/technical/papers/2007-01-4209 “Control System Development for the Diesel APU in Off-Road Hybrid Electric Vehicle”, Rui Chen - Tsinghua University Yugong Luo - Tsinghua University, 2007	G	Available from SAE International	APU in HEV
173	“Nanotechnology and the environment: A European perspective”, DG Rickerby, M Morrison, Institute for Environment and Sustainability, and Institute of Nanotechnology, November 2006	G	ScienceDirect	Sustainability of Li-ion and super capacitors
174	“Assessment of the sustainability of battery technologies through the SUBAT project”, P Van den Bossche, Erasmus Hogeschool Brussel, Nijverheidskaai	G	Web	Sustainability of different batteries

Burke Andrew, *Energy Storage in Advanced Vehicle Systems*, <http://gcep.stanford.edu/pdfs/ChEHeXOTnf3dHH5qjYRXMA/14_Burke_10_12_trans.pdf> (Davis: UC-D, 2005)

Appendix B: Battery Types and Characteristics

The information presented in this Appendix is compiled from the following reference,

http://www.thermoanalytics.com/support/publications/batterytypesdoc.html

HEV Battery Types

The function of the battery in a HEV may be varied. The battery may be a major power source, or may be used in conjunction with the primary power source(s) to level out the supply of power to the drivetrain. As a consequence, the amount of battery power aboard a HEV may vary between a single battery and a pack of many batteries connected together. When using batteries as a primary source of power, the HEV designer is concerned with the mass and volume of the battery pack required to meet the power and energy needs of the vehicle. The drive to achieve high power and high energy densities has led the HEV community to investigate many types of batteries. These new battery types also promise greater cycle depth, power and energy capacity.

BATTERY RATINGS AND CHARACTERISTICS

The decision as to which battery type should be used in a HEV application depends on how well the characteristics of that battery match the needs of the HEV design. The battery characteristics of most concern to the HEV designer are:

- **CAPACITY:** The battery capacity is a measure of how much energy the battery can store. Batteries do not simply serve as a bucket into which one dumps electricity and later extracts it. The amount of energy that can be extracted from a fully charged battery, for instance, depends on the temperature, rate of discharge, battery age, and battery type. Consequently it is difficult to specify a battery's capacity using a single number. There are primarily three ratings that are used to specify the capacity of a battery:

  Ampere-hour: The Ampere-hour (Ah) denotes the current at which a battery can discharge at a constant rate over a specified length of time. For SLI (starting-lighting-ignition) batteries that are commonly used in cars, the standard is to specify Ampere-hours for a 20 hours discharge. This standard is denoted by the nomenclature of C/20. A 60 Ah C/20 battery will produce 60 Ah for a 20 hour discharge. This means that the new and fully charged battery will produce 3 Amps for 20 hours - it does not mean that the battery can produce 6 Amps for 10 hours (that would be signified by a C/10 60 Ah rating).

  Reserve Capacity: The reserve capacity denotes the length of time, in minutes, that a battery can produce a specified level of discharge. A value of 35 minutes at 25 Amps for the reserve capacity for a battery means that the fully charged battery can produce 25 Amps for 35 minutes.

  kWh Capacity: The kWh capacity metric is a measure of the energy (Volt * Amps * Time) required to fully charge a depleted battery. A depleted battery is usually not a fully discharged battery; a 12 V car battery is considered depleted when its voltage drops to 10.5 V. Similarly, a 6V battery is usually considered depleted when its voltage drops to 5.25 V.

None of these capacity ratings completely describe the capacity of a battery. Each one is a measure of the capacity under specific conditions. The performance of a battery in an actual application may vary substantially due to different discharge/recharge rates, battery age, cycle history, and/or temperature.

- **VOLTAGE:** By definition a battery consists of two or more cells wired together. A lead-acid type cell produces approximately 2.1 V. A three cell lead-acid battery thus produces 6.3 V (6.3 = 2.1 * 3) and a six cell lead-acid battery produces 12.6 V. For a battery with fill caps, the number of cells can be determined by counting the number of fill caps. The voltage rating is that of a fully charged battery; its voltage will decrease as the battery is discharged.

- **CYCLE DEPTH:** Fully discharging a battery often destroys the battery or, at a minimum, dramatically shortens its life. Deep-cycle lead-acid batteries can be routinely discharged down to 15-20% of their capacity - this represents a depth of discharge (DOD) of 85 to 80%. These deep-cycle batteries are constructed with thick plates for the cathodes and anodes in order to resist warping whereas in conventional lead-acid batteries the plates are paper-thin. Regardless of whether or not the battery is deep-cycle or not, deep discharges shorten the life of a battery. A deep-cycle battery that can last 300 discharge-recharge cycles of 80% DOD (depth of discharge) may last 600 cycles at 50% DOD.

- **WEIGHT/VOLUME:** The designer must consider the weight and volume of the battery pack during the vehicle design process. Different battery types will provide the designer with different energy and power capacities per given weight or volume. The key ratings to consider are the Specific Power/Energy and the Power/Energy densities. These ratings reveal how much power or energy the battery will provide per given weight or volume.

- **ENERGY DENSITY/SPECIFIC ENERGY:** Energy density is a measure of how much energy can be extracted from a battery per unit of battery weight or volume. By default, deep-cycle batteries provide the potential for higher energy densities than non-deep-cycle varieties since more of the energy in the battery can be extracted (e.g. larger acceptable DOD).

- **POWER DENSITY/SPECIFIC POWER:** Power density is a measure of how much power can be extracted from a battery per unit of battery weight or volume. Using the analogy of a car's fuel system, the energy density is analogous to the size of the fuel tank and the power density is analogous to the octane of the fuel.

- **OPERATING TEMPERATURE:** Batteries work best within a limited temperature range. Most wet-cell lead-acid batteries perform best around 85 to 95 F. At temperatures above 125 F, lead-acid batteries will be damaged and, consequently, their life shortened. Performance of lead-acid batteries suffers at temperatures below 72 F; the colder it is the greater the degradation in performance. As the temperature falls below freezing (32 F), lead-acid batteries become sluggish - the battery has not lost its energy; its chemistry restrains it from delivering the energy. Batteries can also freeze. A fully charged lead-acid battery can survive 40 to 50 degrees below freezing, but a battery with a low state of charge (SOC) can freeze at temperatures as high as

30 F. When the water in a battery freezes it expands and can cause irreparable damage to the cells.

- **SULPHATION:** A low state of charge (SOC) in a lead acid battery can lead to sulphation that can seriously damage the battery. In a low SOC state, lead crystals that are formed during discharge can become so large that they resist being dissolved during the recharge process. This prevents the battery from being recharged. Sulphation can occur when the battery is left at a low SOC for a long period of time.
- **SELF-DISCHARGE:** A battery that is left alone will eventually discharge itself. This is particularly true of secondary (rechargeable) batteries as opposed to primary (non-rechargeable) batteries.

BATTERY TYPES

There are many types of batteries that are currently being used - or being developed for use - in HEVs.

Battery Type	Energy Density [Wh/kg]	Power Density [W/kg]	Cycle Life	Operating Temp. [C]	Storage Temp. [C]	Self Discharge Rate [% per month]	Maturity	Current Cost [$/kWh]	
Lead-Acid	25 to 35	75 to 130	200 to 400	-18 to +70	ambient	2 to 3	production	100 to 125	
Advanced Lead Acid	35 to 42	240 to 412	500 to 800				production		
Nickel-Metal Hydride	50 to 80	150 to 250	600 to 1500				prototype	525 to 540	1
Nickel-Cadmium	35 to 57	50 to 200	1000 to 2000	-40 to +60	-60 to +60	10 to 20	mature	300 to 600	
Lithium-Ion	100 to 150	300	400 to 1200				laboratory		
Zinc-Bromide	56 to 70	100	500					300	
Lithium Polymer	100 to 155	100 to 315	400 to 600	60 to 100			laboratory		
NaNiCl	90	100		270 to 350 (300 optimal)		400	prototype		
Zinc-Air	110 to 200	100	240 to 450				prototype	300	
Vanadium Redox	50	110	400					300	

Table 12 lists these types along with their common characteristics. The types are listed in descending order of popularity for use in HEVs, with the most popular choices at the top of the table. Typically the Energy Density, sometimes called Specific Energy, is rated at the C/3 rate (i.e. 3 hour discharge). Typical conditions for the Power Density or Specific Power rating is a 20 second discharge to 80% DOD. Cycle life is usually measured at 80% DOD.

Battery Type	Energy Density [Wh/kg]	Power Density [W/kg]	Cycle Life	Operating Temp. [C]	Storage Temp. [C]	Self Discharge Rate [% per month]	Maturity	Current Cost [$/kWh]	Future Cost {$/kWh]	Principal Manuf.	Other Notes
Lead-Acid	25 to 35	75 to 130	200 to 400	-18 to +70	ambient	2 to 3	production	100 to 125	75	Trojan, Hawker, Exide, Interstate	
Advanced Lead Acid	35 to 42	240 to 412	500 to 800				production			Delphi, Horizon, Electrosource	Potential: 55 Wh/kg, 450 W/kg, and 2000 cycle life
Nickel-Metal Hydride	50 to 80	150 to 250	600 to 1500				prototype	525 to 540	115 to 300	Panasonic, Ovonic, SAFT	Potential: 120 Wh/kg, and 2200 cycle life
Nickel-Cadmium	35 to 57	50 to 200	1000 to 2000	-40 to +60	-60 to +60	10 to 20	mature	300 to 600	110	SAFT	Potential: 2200 cycle life
Lithium-Ion	100 to 150	300	400 to 1200				laboratory			SONY, SAFT	Potential: 1000 Wh/kg
Zinc-Bromide	56 to 70	100	500					300			
Lithium Polymer	100 to 155	100 to 315	400 to 600	60 to 100			laboratory		100		
NaNiCl	90	100		270 to 350 (300 optimal)		400	prototype			AEG Anglo	
Zinc-Air	110 to 200	100	240 to 450				prototype	300	100	Liquid Fuel Ltd	
Vanadium Redox	50	110	400					300			

Table 12 Battery types

Brief Description of Each Battery Type

- **Lead-Acid:** Low cost and available now vs low energy density and only moderate cycle life. The lead acid battery is composed of lead plates of grids suspended in an electrolyte solution of sulphuric acid and water. These batteries can be ruined by completely discharging them.

- **Advanced Lead-Acid:** Available now. Longer cycle life than conventional lead acid. Valve regulated lead-acid (VLRA) batteries are showing great promise.

- **Nickel-Cadmium:** Higher energy density than lead-acid and available now vs cost. memory effect and toxicity. The nickel-cadmium battery is composed of a nickel hydroxide cathode and a cadmium anode in an alkaline electrolyte solution. If these batteries are discharged only partially before recharging, the cells have a tendency to act as if they have a lower storage capacity than they are actually designed for; this is the memory effect. Nickel-cadmium batteries can often be restored to full potential (i.e. "full memory") with a few cycles of discharge and recharge. These batteries are often used to power small appliances, garden tools, and cellular telephones. Batteries made from Ni-Cd cells offer high currents at relatively constant voltage and are tolerant of physical abuse.

- **Nickel-Metal Hydride:** High efficiency and environmentally friendly. The nickel-metal hydride battery is composed of a hydrogen storage metal alloy, a nickel oxide cathode, and a potassium hydroxide electrolyte. These batteries can be quickly recharged. They have been used for a long time to power flashlights, lap-top computers, and cellular telephones.

- **Lithium-Ion:** Lithium seems an ideal material for a battery: it is the lightest metal in addition to having the highest electric potential of all metals. Unfortunately, lithium is an unstable metal, so batteries that use lithium must be made using lithium ions (such as lithium-thionyl chloride). Even so, dangers persist with lithium-ion batteries. Many of the inorganic components of the battery and its casing are destroyed by the lithium ions and, on contact with water, lithium will react to create hydrogen which can ignite or can create excess pressure in the cell. If the lithium melts (melting point is 180 C), it may come into direct contact with the cathode, causing violent chemical reactions. As a consequence, lithium batteries are often limited to small sizes. Portable devices, such as notebook computers, smart cards, and cellular telephones, are often powered by lithium ion batteries. These batteries have no memory effect and do not use poisonous metals, such as lead, mercury or cadmium.

- **Zinc-Bromide:** High energy density and long cycle life vs complex and toxicity. Zinc-bromine batteries pass two oppositely charged liquids through an ion-exchange membrane to produce electricity. The electrolyte is usually a zinc bromide-potassium chloride solution. Bromine, in both liquid and vapor form, is toxic and a strong irritant. The required pumping system makes the system complexity.

- **Lithium Polymer:** Lithium-polymer cells have shown great promise, at the laboratory level, in fulfilling the need for a battery of high specific power and energy in electric vehicle applications. A major uncertainty is whether heat generated in Li-polymer batteries during discharge at high power can be transported to the outside without excessive internal temperatures occurring. A second concern is whether lithium-polymer batteries can be brought up to operating temperatures in times that are acceptable to consumers.

- **Sodium Nickel Chloride:** In its charged state, the cell consists of a negative liquid sodium electrode and a solid positive electrode containing nickel chloride and nickel. The electrodes and electrolyte are encapsulated in a steel cell case which simultaneously functions as the negative pole of the cell.

- **Zinc-air:** High energy density vs short cycle life, low power density and low efficiency. The cathode of this battery is made of porous carbon which absorbs oxygen from the air. The zinc-air battery uses a zinc anode and the electrolyte is a base (rather than an acid), typically potassium hydroxide. Zinc-air batteries have been used in hearing aids for many years.

- **Vanadium Redox:** High efficiency and can be completely discharged without damage vs high cost. The term redox is an abbreviation of "reduction oxidation". This battery, along with the Iron Redox battery, obtains its power when one of the chemicals is reduced (i.e. gains electrons) while the other is oxidized (i.e. loses electrons). This battery is still very much in the development stages but shows great promise for EV use.

There are several other battery types that researchers have considered for HEVs, but their uses are not common. The following are included, listed with their major strengths and weaknesses:

- **Aluminium-air :** long shelf-life and high energy density vs complex and low efficiency. Aluminium-air batteries obtain their energy from the interaction of aluminium with air. The incoming air must be filtered, scrubbed of CO2, and dehumidified; the water and electrolyte must be pumped and maintained within a narrow temperature range - hence the complexity of the battery. The batteries are not electrically recharged but are "refuelled" by replacing the aluminium anodes and the water supply.

- **Iron-air :** high energy density vs complex, short cycle life, and high self-discharge rate. The iron-air battery uses electrodes made of iron and carbon. The carbon electrode provides oxygen for the electrochemical reaction. These batteries can be electrically recharged. Iron-air batteries are significantly affected by temperature; they perform poorly below 0 C.

- **Lithium-iron sulphide:** high energy density vs high operating temperature. The lithium-iron sulphide battery is composed of a lithium alloy anode and an iron sulphide cathode suspended in an electrolyte molten salt solution. A variation of this battery system uses a cathode made of lithium-iron sulphide.

- **Nickel-iron:** high energy density and long life vs high cost and high self-discharge rate. Nickel-iron batteries employ cathodes of nickel-oxide and anodes of iron in a potassium hydroxide solution. Nickel-iron batteries have long been used in European mining operations because of their ability to withstand vibrations, high temperatures and other physical stress. Also known as the Edison battery (invented by Thomas Edison in 1901).

- **Nickel-zinc:** high power density vs short cycle life. The nickel-zinc battery is composed of a nickel oxide cathode and a zinc anode in a small amount of potassium hydroxide electrolyte. Recharging can be tricky in that zinc can be re-deposited in areas where it is not desired, leading to the physical weakening and eventual failure of the electrode..

- **Silver-zinc:** high energy density vs high cost and short cycle life. The cathode in a silver-zinc battery is a silver screen pasted with silver oxide. The anode is a porous plate of zinc, and the electrolyte is a solution of potassium hydroxide saturated with zinc hydroxide. Their high cost results from the amount of silver needed for the construction of these batteries.

- **Sodium-sulphur:** high energy density and high efficiency vs high operating temperature. The battery, unlike most other batteries, uses a solid electrolyte (beta aluminium) and liquid electrodes (molten sulphur and sodium). These batteries require to be heated to around 325 C in order to operate because it is at these temperatures that sulphur and sodium will melt (i.e. become liquid).

- **Zinc-chlorine:** high energy density and long cycle life vs complex, requires refrigeration, and toxicity. Similar to the zinc-bromide battery (bromine and chlorine are both halogens), the zinc-chlorine battery is even more complex since it requires refrigeration during the recharging process to remove heat. Chlorine gas is highly lethal.

- **Zinc-Manganese:** Low peak power output and short cycle life. Zinc-Manganese Dioxide Alkaline Cells: when an alkaline electrolyte--instead of the mildly acidic electrolyte--is used in a regular zinc-carbon battery, it is called an "alkaline" battery.

FACTORS AFFECTING BATTERY PERFORMANCE

TEMPERATURE

Battery performance is highly dependent on temperature. Each type of battery works best within a limited range of temperatures. Concerns related to battery temperature include:

- Poor energy and power extraction performance for temperatures outside the operating temperature range
- Thermal runaway - during high power extraction the temperature of the battery increases which makes further power extraction more difficult and causes subsequent increases in temperature.
- Long heat up times before the battery reaches operating temperature - this is a concern for ambient temperature batteries such as lead-acid in cold environments and also for batteries such as lithium/polymer-electrolyte which requires an operating temperature that is elevated above ambient

The battery temperature can change due to changing current flowing through the internal resistance of the battery. The internal resistance can vary with the changing state of charge (SOC) of the battery. The temperature of the battery can also vary between different cells since the cells in the centre are more insulated from outside convective cooling than the cells at the ends/edges. Consequently, the cells in the centre may see a higher temperature rise than the ones near the outer boundaries of the battery package.

The impact that temperature exerts on battery capacity can be explained using a simple model of the battery electrochemistry. As the temperature increases towards the peak performance-operating temperature the electrolyte viscosity decreases, thus allowing for increased diffusion of ions and hence increased battery performance. As the temperature increases past this peak point, the battery electrodes begin to corrode, leading to a reduced "active" electrode area and thus to fewer electrode reactions and reduced battery capacity.

BATTERY AGE/SHELF LIFE

Corrosion due to age is the main component behind decreased performance in lead-acid type batteries by age.

DEPTH OF DISCHARGE

Batteries are able to maintain their performance longer when they are not deeply discharged regularly

Appendix C: Railway Model for Energy Simulation

High level simulations are possibly the only way to determine the overall performance of the railways when new technologies for energy management and saving are to be assessed and introduced. Batteries and super-capacitors are two of the applications that can be assessed using a high level railway model. The results from the simulator will be used to assess the overall performance of the railways and will feed into a high level cost and economic benefits models that will help the decision making process.

The characteristics of batteries and super-capacitors are inherently non-linear and governed by the level of energy stored, thermal state, rate and depth of charge and discharge, etc. Modelling of theses devices, including the power electronics circuitry, such as a two way dc-dc converter, will be based on developing two-port electrical circuits that exhibit the terminal behaviour under different conditions. These models will be developed in a frequency domain but also will be time dependent (response time in seconds) where the level of energy stored is of prime consideration.

The models for batteries and super-capacitors will then be plugged into the appropriate positions, e.g. on a train or trackside, in a railway simulator. The railway simulator is a standard railway model that is capable of multi train operation and incorporating details of the infrastructures, power supply, train operation and signalling.

Furthermore to manage the energy stored against the operational conditions, control algorithms will be developed to optimise the design and linking of the train operation to the state and capacity of equipments. Such algorithms may include „look ahead" criteria which would integrate the duty cycle as part of the energy management system of the train.

Below is an overview of the railway simulator that will be used in this study. This simulator will be developed and used as a general tool for various studies, including this work.

The simulator incorporates a standard electrified railway with the following main features;

- Double track comprising variable gradient, speed limits, tunnel sections and curvatures.
- Passenger services for metro type timetabling, or main line timetabling with variable passenger loading.
- Modelling of coasting and driving techniques.
- Modelling of disturbances and delays and consequent impact.
- Modelling of mixed electric rolling stock and non-electric diesel or hybrid trains.
- Electrified ac or dc supplies, non-electrified, mixed or discontinuous electrification systems for battery-assisted train operation.
- Electrical network model contains the return path and the bonding configuration, hence capable of determining accessible voltages and touch potentials.
- Models for junctions, crossovers and terminus would enable modelling more complicated railway networks and comprehensive timetabling. This feature however would be postponed to a later stage as it requires detailed modelling of the signalling system.

The model will be capable of handling hybrid and fuel cell vehicles and the effects of various driving techniques, including coasting, optimisation and train regulation. It will have adequate capability for operation modelling such as timetabling and passenger flow. It will also be capable of handling simplified disturbances and delays and the consequent effects. The main focus of the model in this study will be to determine accurately the level of energy consumption.

To investigate the different battery and/or super-capacitor the following modules will be added;

1. Battery and/or super-capacitor assisted electric trains with discontinuous OHL or 3rd rail supply.
2. Hybrid and fuel cell trains, these are non eclectic trains and can be run simultaneously with electric trains.
3. Models for trackside storage devices such as flywheels, batteries, super-capacitors, etc

There are other modules which are available but not directly related to the battery and/or super-capacitor study. These modules include VCR, flywheels and inverters on dc railways. And on ac railways models for SVC, dampers and load balancers will be available. In addition there will be a capability to include any future equipment required. Furthermore the model can be extended relatively easily to cover additional features such as the following,

1. Calculation of fault levels, protection coordination and breaker setting on electrified lines, both ac and dc.
2. Calculation of touch potential under fault conditions, and accessible voltages in normal operation.
3. Calculation of induced voltages in lineside circuits and the level of magnetic fields in the vicinity of the railway line.
4. Determining transient effects such as gapping, short circuits, pantograph bouncing and arcing. For this to work, the initial conditions for the transient will be the steady state node voltages and branch currents at the moment of the transient event.

Example:

Implementation of electric-hybrid vehicles: For battery and/or super-capacitor assisted trains operating on discontinuous, or gaps, in the supply, there will be an additional component introduced in the core to represent locations such as cross-overs, level crossing, bridges, etc. where no supply is provided. This is in addition to adding the main module for battery and/or super-capacitor equipments that are mounted on the train. This module is generic in that the battery and/or super-capacitor are modelled as energy storage devices having a defined capacity. Limitations in charging and discharging mechanisms will be defined for each type of battery and/or super-capacitor considered.

In terms of control, one criterion is to keep the battery and/or super-capacitor fully charged as long as the train is operating from the supply in order to be able to provide the energy required through gaps. However the same battery and/or super-capacitor can be used to store regenerative braking energy particularly on dc. Hence the control strategy would be to operate the battery and/or capacitor at some quiescent point that would enable both storing energy during braking and providing energy for discontinuous supply operation, whichever is encountered during the operation.

Consequently, a control algorithm will be required to relate the duty cycle, e.g. „look ahead" algorithm, to the level of the energy stored. It should be noted that modelling of battery and/or super-capacitor equipment can be used generically for other means of storage such as flywheels and hydraulic accumulators. The only difference is to redefine the terminal characteristics and the control strategy for the mechanical devices. The numerical simulation applies both ways equally in the same fashion.

Appendix D: Battery and Super Capacitor Data

Battery Type	Lead-Acid	NiMH	Li-Ion (EV)	Li-Ion (HEV)	S Capacitor
Specific Power to Energy P/E	6	2.7	7	36	>1,500
No of cycles at 80% DOD	400	400	2,500	3,000	>1,000,000
Specific Cost ($/Wh)	0.05	1.00	1.20	1.20	4.93

Table 13 Ref 55 2007

Battery Type	Lead-Acid	NiCd	NiMH	Li-Ion
Specific Energy (Wh/kg)	30-40	50-55	40-80	110-150
Efficiency %	65-75	65	65	>90
Lifetime at 80% DOD cycle	>1,000	800-1,500	800-1,500	2,000-3,000
Cost $/kWh	100-150	>320	>320	>500
Self discharge % per month	-	2-30	30-35	3-5

Table 14 Ref 78 2006

Battery Type	Lead-Acid	NiCd	NiMH	Li-Ion	ZEBRA
Specific Energy (Wh/kg)	34	45	65	110	120
Specific Power (W/kg)	75	120	90	220	180
Self discharge % per month	8	20	30	10	None
Lifetime at 80% DOD cycle	500	1,000	500	400	2,000
Efficiency %	70	80	80	85	90
Cost £/kWh	105-175	200-300	250-350	250-1,000	70-270

Table 15 Ref 67 2005 ZEBRA™ is Sodium Nickel Chloride battery Na-NiCl

Battery Type	Lead Acid	NiMH	Li-Ion	S Capacitor
Specific Energy (Wh/kg)	40	40-70	30-130	6
Specific Power (W/kg)	300	200-700	30-1,400	500
Lifetime cycle	500	1,000	1,000	>100,000

Table 16 Ref 60 2003

Battery Type	Lead acid	Ni-Cd	Ni-MH	Zn-Br2	Na-S	Na-NiCl	Li-Ion
Working Temp C^{o}	0, 45 -20,-60	0, 50 -40,-60	-40, 50	20, 40 10, 60	300, 350 250, 370	300, 350 285, 370	-40, 60
Specific Energy (Wh/kg)	161	236	300	430	794	795	275
Specific E at 2h discharge	20-30	40-55	50-60	50-70	80-100	90-120	90-140
Energy density Wh/L	60-80	60-90	100-150	60-70	110-120	120-130	150-200
Specific Power (W/kg)	75-100	120-150	140-200	80-100	150-200	150-200	350-400
Cell Voltage charged V	2.1	1.35	1.35	1.79	2.58	2.08	3.6

Table 17 Ref 71 2000

Battery Type	Lead Acid	S Capacitor	Electrolytic Capacitor
Charge Time	1-5 hrs	0.3-30 s	1ms-1us
Discharge time	0.3-3 hrs	0.3-30 s	1ms-1us
Specific Energy (Wh/kg)	10-100	1-10	<0.1
Specific Power (W/kg)	<1,000	<10,000	<100,000
Lifetime cycle	1,000	>500,000	>500,000
Efficiency charge/discharge	70-85	85-98	>95

Table 18 Ref 110 recent

Battery Type	Lead Acid	Lithium Polymer
Specific Power (W/kg) at 50% SOC	107	930
W/L at 50% SOC	233	1860
Specific Energy (Wh/kg) at 2h rate	27	80
Wh/L at 2h rate	59	160

Table 19 Ref 13 2003

	Type	VRLA	TMF	Ni-MH	Li-Ion	Li-Pol	EDLC
EV	Temperature Range C^o	-30, 70	0, 60	0, 40	0,35	0, 40	-35, 65
	Specific Energy E (Wh/kg)	35		70	90	140	
	Specific Power P (W/kg)	350		180	220	300	
	No of cycles C At 80% DOD	400		1,200	600	800	
	Ratio of P/E	7		2.6	2.4	2.1	
	Energy Life E * C * 0.8	11,200		67,200	43,200	89,600	
HEV	Specific Energy E (Wh/kg)	25	30	40	65		4
	Specific Power P (W/kg)	80	800	1,000	1,500		9,000
	No of cycles C at 80% DOD	300		5,500	2,500		500,000
	Ratio of P/E	3.2	27	25	23		2,250
	Energy Life E * C * 0.8	6,000		176,000			1,600,000

Table 20 Ref 71 2000, VRLA Valve Regulated Lead Acid, TFM Thin Film Foil Lead Acid, EDLC Electrochemical Double Layer Capacitor, EV Electric Vehicle, HEV Hybrid Electric Vehicle

Battery Type	Wh/kg
Lead Acid	35
NiCd	45
NiMH	90
Li-Ion	150
Gas oil	12,000

Table 21 Ref 124 2005

	Ness 3500F S Capacitor	M3 DC FPS Flywheel	Hydraulics M/G
kWh	0.622	0.42	0.26
Max Power kW	260	200	300
Weight kg	267	500	230
Volume L	370	866	160
Voltage	300-600	--	200-800
Efficiency	94	90	70-75
Wh/kg	2.33	0.84	1.13
Wh/L	1.7	0.49	1.6
W/kg @ 90%	970	400	1875

Table 22 Ref 125 2005

	$/kg	$/kWh	$/kW
Advanced Lead acid	4.0	200	10.0
NiMH	22.5	500	45.0
Lithium Ion	45	700	41.0
Super capacitor	18.0	3570	18.0

Table 23 Ref 125 2005

	Wh/kg	W/kg	DOD (Indicative)
NiMH battery	65	200	80%
	50	250	60%
	40	450	20%
Lithium Ion battery	130	450	80%
	100	650	60%
	70	1,200	20%
Super Capacitor	5	2,500	75%

Table 24 Ref 125 2005 Trade-off between energy density and power density. DOD Depth of Discharge determined by the size of battery

S Capacitor Type	Rated voltage (V)	Capacity C (F)	ESR R m Ω	RC (sec)	Wh/kg	W/kg	W/kg match Ω	Weight (kg)	Volume (L)
Maxwell	2.5	2700	0.32	0.86	2.55	784	6975	0.70	0.62
Ness	2.7	10	25.0	0.25	2.5	3040	27,000	0.0025	0.0015
Ness	2.3	120	21.0	2.5	3.8	282	3,700	0.17	0.01
Ness	2.7	1800	0.55	1.0	3.6	975	8674	0.38	0.277
Ness	2.7	3640	0.30	1.1	4.2	928	8010	0.65	0.514
Ness	2.7	5085	0.24	1.22	4.3	958	8532	0.89	0.712
Asahi Glass	2.7	1375	2.5	3.4	4.9	390	3471	0.21	0.151
Panasonic	2.5	1200	1.0	1.2	2.3	514	4596	0.34	0.245
Panasonic	2.5	1791	0.30	0.54	3.44	1890	16,800	0.31	0.245
Panasonic	2.5	2500	0.43	1.1	3.70	1035	9,200	0.395	0.328
EPCOS	2.5	220	3.0	0.66	2.76	1126	10,000	0.052	0.042
EPCOS	2.5	2790	0.15	0.42	3.46	2055	18,275	0.57	0.377
Montena	2.5	1800	0.50	0.90	2.49	879	7,812	0.40	0.30
Montena	2.5	2800	0.39	1.1	3.33	858	7,632	0.525	0.393
Okamura	2.7	1350	1.5	2.0	4.9	650	5,785	0.21	0.151
ESMA	1.3	10,000	0.275	2.75	1.1	156	1,400	1.1	0.547

Table 25 Ref 125 2005, Summary characteristics of different super capacitor manufacturers, ESR Equivalent Series Resistance

RSSB Research Programme
Block 2 Angel Square
1 Torrens Street
London
EC1V 1NY

research@rssb.co.uk

www.rssb.co.uk/research/rail_industry_research_programme.asp

Research Programme

Engineering

Energy storage systems for railway applications
Phase 2: OHL electrification gaps

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Energy storage systems for railway applications
Phase 2: OHL electrification gaps

Executive Summary

This report presents an investigation into coasting, discontinuous and discrete electrification schemes, as part of Phase 2 of the RSSB R&D research project T779, *Energy Storage Systems for Railway Applications*.

The main objective of this report is to assess the feasibility of these schemes and to size and cost the storage devices required against nature of gaps introduced and classified according to different train types.

Different types of storage devices and different trains are considered for different gap natures. Gaps are classified according to lengths, numbers and the infrastructure characteristics. A cost benefit analysis study for an assumed hypothetical discontinuous electrified system employing super capacitors is also presented.

The report presents a numerical simulator, called ESSRA, which is capable of assessing different electrification schemes with multiple gaps in the overhead line (OHL). The software is available on CD and can be run on a standard PC. A copy can be obtained from RSSB.

This report concludes that discontinuous electrification, in conjunction with coasting, is feasible. Trains can be operated on such routes, relying on coasting alone but will require a special operating procedure. Trains may be fitted with either super capacitors for frequent recycling pattern of operation, or small emergency batteries used only when required. Frequent cycling may be used for cases where gaps are required at, or near stations, and also can be used for capturing braking energy. Emergency battery storage may be used should trains stop within a gap during unscheduled events.

An indicative assessment of the business case for discontinuous electrification suggests that these schemes are viable using existing technologies. However, it is recommended that a study is undertaken to accurately estimate the cost of electrifying a specific route with or without discontinuities. This is a key parameter in determining the feasibility of such a system.

Discrete electrification, given the available energy storage technologies, seems difficult to justify. Whether using state of the art lithium ion batteries or conventional lead acid batteries, the

scheme does not seem viable. One of the problems with this scheme is that the entire fleet of trains must be fitted with storage devices, which introduces severe constraint on operation. However, future technologies may hold a key to make this application possible, but this is very difficult to predict at this stage.

Abbreviations

CBA	Cost Benefit Analysis
DEMU	Diesel Electric Multiple Unit
DOD	Depth Of Discharge
EDLC	Electrochemical Double Layer Capacitor
ESSRA	Energy Storage Systems Railway Applications
ESR	Equivalent Series Resister
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IGBT	Insulated-Gate Bipolar Transistor
Li-Ion	Lithium Ion Battery
MLC	Magnetically Loaded Composite
NiMH	Nickel Metal Hydride Battery
NPV	Net Present Value
OHL	Over Head Line
PWM	Pulse Width Modulation
SGO	Single Gap Operation
SOC	State Of Charge
STR	Single Train Run
SVM	Space Vector Modulation
VSI	Voltage Source Inverter

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Energy storage systems for railway applications

Phase 2: OHL electrification gaps

1 Introduction

This report presents an investigation into coasting, discontinuous and discrete electrification schemes, as part of Phase 2 of the RSSB R&D research project T779 *Energy Storage Systems for Railway Applications*.

The main objective of this report is to assess the feasibility of these schemes. The assessments include determining the size and cost the storage devices required against the nature of gaps, lengths and locations of gaps along the route, and operating different types of trains (suburban, regional intercity and freight).

An overview of storage devices is provided in section 2 and issues associated with hybridisation of electric rail vehicles are shown in section 3.

The study presents an assessment of discontinuous electrification schemes, in conjunction with coasting. This is shown in section 4. A case study of an assumed system is presented in section 5. The case for discrete electrification is discussed in section 6.

A numerical simulator, called ESSRA, capable of assessing different electrification schemes with multiple gaps in the OHL, is presented in section 7. The software is available on CD and can be run on a standard PC. A copy can be obtained from RSSB.

2 Review of energy storage systems

2.1 Energy storage devices considered

The storage devices considered in this study are batteries, super capacitors and flywheels. Hydraulic storage devices are not considered as the integration of such devices cannot be investigated in the same manner[1].

The general illustration of storage devices capabilities can be expressed using Ragon plots as shown in Figure 1. These plots show the specific power and specific energy densities expressed as Wh/kg and W/kg respectively. Ragon plots do not show the cycling (useful life) capability, cost or the volumetric density of the storage devices. Nevertheless, they are a useful means for comparison.

Figure 1 shows a number storage of devices including lead acid, nickel metal hydride NiMH, lithium-ion batteries, and super capacitors. The batteries and super capacitors shown are commercially available and usually manufactured in small cell units. A storage device can be constructed using a combination (possibly in hundreds) of cells in series and parallel configurations.

Figure 1 also shows modern flywheel characteristics. This technology is based on MLC carbon fibre flywheel running at very high speeds. Nano technology devices are also shown. These technologies may be considered as possible future products in the form of pseudo batteries or asymmetrical double layer super capacitors. There are a number of prototype nano devices demonstrated recently, but these are not commercially available. A comparison is also made with internal combustion engines and fuel cells.

The specific power (P) represents the ability to accelerate, or to provide an instantaneous power demand, compared with the specific energy (E) that provides the range. Of specific interest, is the ratio E/P which gives the discharge time of the device, and the ratio P/E which provides an indication of pulse power to energy stored capability.

---

[1] Usually hydraulic storage devices are mechanically integrated with, and considered part of, the internal combustion engine. It is purely dependent on the manufacturer design and therefore will not be considered.

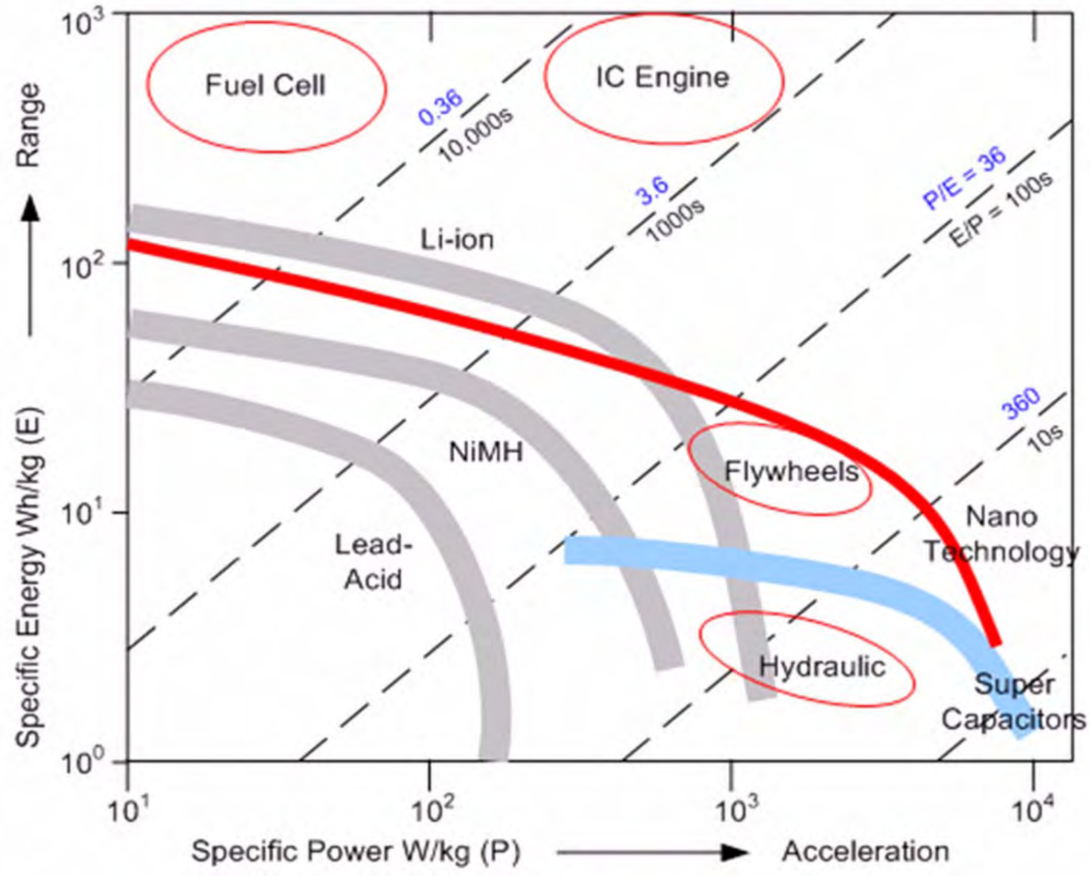

Figure 1 - Ragon plots of different energy storage devices

2.1.1 Batteries and Super Capacitors

Batteries and super capacitors are manufactured by choosing an optimum point on the Ragon plot for P and E depending on power and energy requirements. The power capability P can be increased (for example by maximising the size of the electrodes to be able to conduct larger currents) at the expense of permitting smaller volume of electrolyte. This results in lower level of energy stored, i.e. low specific energy E. This flexibility in manufacturing, both for batteries and super capacitors, results in that the characteristics can take locus shapes as shown in Figure 1. It illustrates that the higher the E the lower the P, and vice versa.

For the purpose of this study two types of batteries and two types of super capacitors have been chosen, for (a) power orientated devices, i.e. maximising P, and (b) energy orientated devices, i.e. maximising E. The chosen devices (see Table 1) are named as, 'Batt_1' and 'Batt_2' for high power and high energy lithium ion battery respectively, 'S_Cap1' and 'S_Cap2' for high power and high energy respectively. All these devices are commercially available. The Ragon plots of these devices are shown in Figure 2.

Storage Name	Description	W/kg	Wh/kg	Wh/L
‘Batt_1’	high energy orientated Li-ion battery commercially available	450	130	150
		650	100	
‘Batt_2’	high power orientated Li-ion battery commercially available	930	80	150
		1200	70	
‘S_Cap1’	high energy orientated super capacitor commercially available	650	4.9	1.7
		958	4.3	
‘S_Cap2’	high power orientated super capacitor commercially available	2055	3.46	1.7
		8929	2.5	
‘Flywheel’	theoretical MLC flywheel (scaled version of the racing car)	1625	25	45
‘Nano’	prototype nano technologies, not available commercially. Note poor efficiency is assumed	8000	27	--

Table 1 - Energy devices assumed in this study

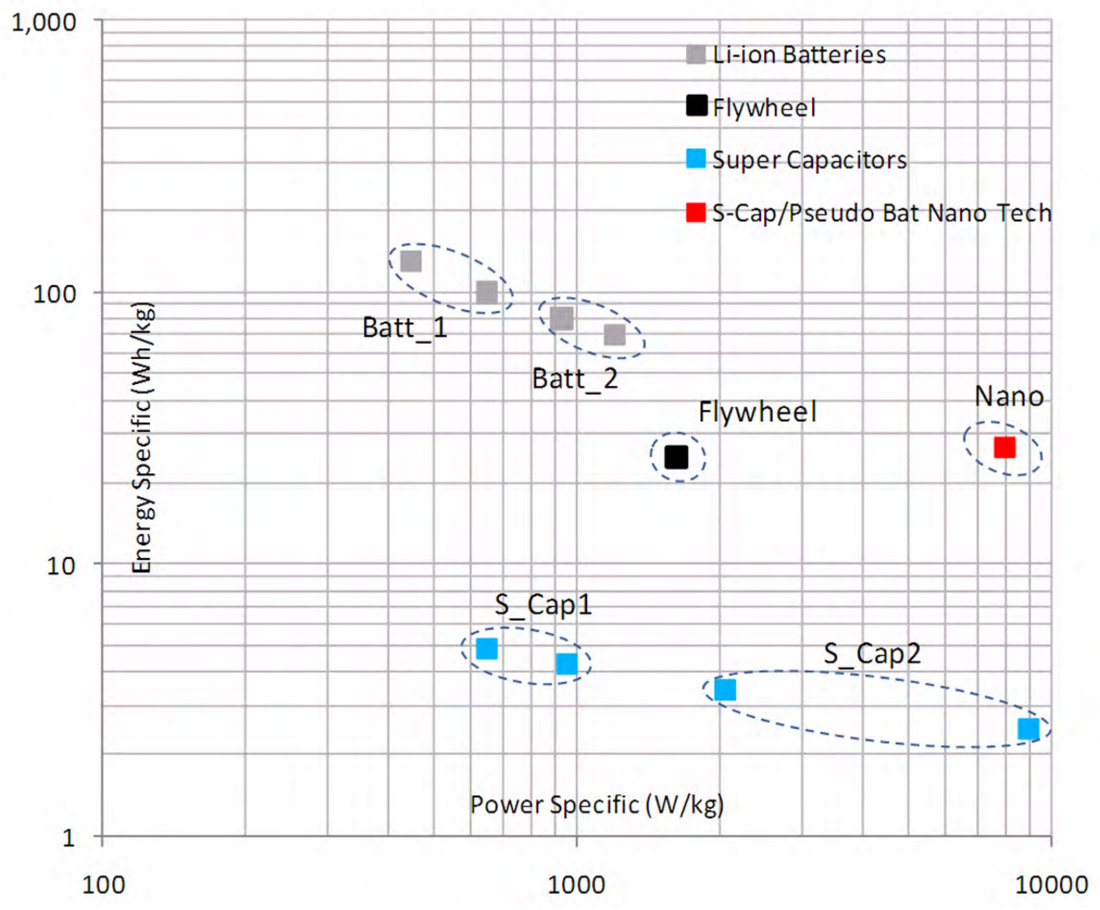

Figure 2 - Ragon plots of specific energy storage devices

2.1.2 Flywheels and Nano Technologies

The Flywheel used in this study is based on theoretical characteristics of Magnetically Loaded Compound (MLC) flywheel employing carbon fibre. The flywheel usually is scalable and the data chosen in Table 1 are based on scaling up a Formula 1 racing car version of the flywheel (see Figure 2).

The term 'Nano' in Table 1 is chosen for prototype nano technologies which have been demonstrated to work, but not available commercially yet, and is used in the analysis to demonstrate the possible future trends and improvements in these technologies. The Ragon plots of these devices are shown in Figure 2 also.

2.2 Technologies Comparison

The energy stored in a super capacitor is proportional to the square of the voltage. Super capacitor systems are usually designed to cease releasing energy when the voltage reaches half the maximum rating. Beyond this limit excessive losses would result and it would require unduly complex controller to work. With a desirable minimum voltage of half of that of the rating, the available energy is 75% of the maximum stored (1-0.52).

There is analogy between super capacitors and flywheels in that the energy stored is proportional to the square of the speed, and the minimum practical speed cannot be dropped below half the maximum. In both cases, therefore, the available energy is 75% of the maximum stored. Both devices also share high power to energy P/E ratio capability, meaning the device can deliver high power for short durations, but with limited energy storage capability.

Batteries, on the other hand, have considerably larger energy storage capacity and significantly lower P/E ratio. Unlike super capacitors batteries, usually, are not designed for frequent and deep discharging. The useful life of a battery can be shortened considerably with deep discharging. The life of a battery is also affected by the rate of discharging currents and temperatures. Therefore the method of operating a battery determines its useful life. In comparison super capacitors are generally more robust, have longer life and can operate with frequent discharging at substantial discharging rates. Flywheels in this regard share similar characteristics as super capacitors.

However, flywheels require intensive and regular maintenance compared with batteries and super capacitors which are almost maintenance free (apart from regular inspection). The materials used in flywheels are conventional in nature, and as such recyclability is easier. In comparison, batteries and super capacitors are made of scarce materials, and recyclability is not very well established.

The efficiency of a storage device is an important factor in the design. It affects the amount of available energy, and more importantly it determines the cooling requirement. There are two types of losses, converter losses and storage device losses. Losses in the storage device can be approximated as the square of the charging current multiplied by an Equivalent Series Resistance (ESR). As such, the efficiency drops with larger charging currents. For this reason the power rating of a storage device (determined by charging rate) is a key parameter in the design. Efficiencies of up to 90% for both super capacitors and lithium ion batteries have been reported, which were most likely measured at relatively low levels of charging currents. With higher load demands the efficiency will clearly drop, possibly linearly, with the load. For modern MLC flywheels the efficiencies reported are up to 98%. Losses in the flywheel are incurred in the bearings and stator windings only (rotor losses are negligible due to vacuum and MLC).

The cost of storage devices is, generally, high. It is difficult to relate the cost of different devices to a common base because the operating parameters vary widely between different devices. Table 2 shows indicative figures of cost of batteries and super capacitors (prices have gone down since). These figures are the cost of the cells alone without the additional control circuitry and packaging required. For example, a lead acid battery costs less than 1/10th of lithium in weight, but it is 1/3rd in terms of energy storage. Note also super capacitors are more expensive than batteries per energy unit, but cheaper per a unit of power.

	\$/kg	\$/kWh	\$/kW
Advanced Lead acid	4.0	200	10.0
NiMH	22.5	500	45.0
Lithium Ion	45.0	700	41.0
Super capacitor	18.0	3570	18.0

Table 2 - Indicative costs of the storage cells without the additional ancillaries, 2005 prices.

There is also the issue of self discharge which is important in cases where a train may stop within a gap for considerably long time, and hence a risk of losing the stored energy by self discharge. Super capacitors and flywheels may suffer from this problem. The stored energy may self discharge within hours in a super capacitor, and for flywheels it may be lost within tens of minutes. This problem is less severe in batteries where the self discharge may be measured in weeks or months.

The relative merits of three energy storage devices, lithium ion, super capacitor and flywheel are summarised in Table 3.

	Li-Ion Batteries	**Super Capacitors**	**Flywheels**
Volume density Wh/L	150	1.7	29
Current cost	Expensive	Expensive	Relatively cheaper
Usable energy	10-80% depend DOD	~ 75%	~ 75%
Specific energy Wh/kg	450 - 1200	2.5 - 4.9	25
Specific power W/kg	80 - 130	650 - 8900	1625
Cycling	3-10k depend on use	> 1M	> 10M
Useful life (years)	3–10 depends on use	> 20	~ 30 + maintenance
Maintenance	Small	None	Extensive
Sustainability	scarce	limited	Conventional material
Recycling	Little is known	Little is known	Could be recyclable
Hazardous materials	Low level	Low level	None
Safety	Relatively safe	Relatively safe	Unknown
Reliability	Good	Good	Unknown
Package	Flexible	Flexible	Compact single unit
Integration	dc-dc converter	dc-dc converter	dc-ac inverter
Operating temp. C^o	-20 to +40	-20 to +40	-40 to +55
Self discharge	Few days	~ 10 hours	~ 1 hour
Rating	500 – 700 Vdc	200 – 600 Vdc	20,000 – 50,000 rpm
Round efficiency %	~ 90	~ 90	~ 98

Table 3 - Relative merits of batteries, super capacitors and flywheels

2.3 General Considerations

Most of known energy storage rail applications are one of two types; either on the trackside of dc railway to recover braking energy and/or to stabilise line voltage, or dc train onboard storage for recovering regenerative braking energy (see section 13 for selected applications).

Recently onboard storage devices are being introduced to self power the train. The Nice tram (France) is a good example. It employs NiMH battery to power the tram through substantial distances of gaps in the dc supply (two gaps 470m and 440m in length). There are also other trials of self powered trains elsewhere in Europe. Generally, the rail vehicle in these applications operates at reduced performance when powered from the storage device to conserve energy, hence minimising storage size requirements.

The phase 2 research under the current T779 project involves investigation into discontinuous and discrete electrification schemes. In these applications the required devices are substantially larger than any known rail application. Also, large numbers of these devices would be required to equip the fleet of trains operating on these schemes. The sizes, and numbers, of the storage devices required have never been built or proven before in any known application. Consider, for example, a freight train operating through a few hundred metres gap, the size of storage required would be in the order of a few tonnes of battery weight at substantial cost. Such devices would be required on every train in service that is likely to operate on that route. For discrete electrification the only devices of choice are batteries of considerable sizes. Obviously, the immediate thought would be to render the business case infeasible, as batteries are expensive and have limited life.

The large number and size of storage devices required (volume and weight), and the associated cost, would be a determining factor in the business case of these applications. One of the main problems with electric hybridisation of rail vehicle is that every train must be fitted with appropriate storage device to be able to operate on these schemes, particularly discrete electrification. The electrification system must be designed alongside the trains which must be compatible with the infrastructures. The resulting system does not lend itself to evolve by means of introducing or adding equipments gradually[2].

There is a need for integrated design of the entire system including trains, power supply and possibly the signalling system. Trains operating on these schemes will have to be compatible with the electrification infrastructures. It will be difficult, if not impossible, to run standard trains on these lines.

The main risks associated with discontinuous and discrete electrification schemes are trains being stranded in the gap with no energy available for self powering. Also, there could be undesirable effects associated with frequent dropping and raising of pantographs (see T778, Reference 4). In addition, given the large sizes and numbers of storage devices, there will be inevitably problems with sustainability, reliability, cost, suppliers, etc. of the storage devices involved.

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[2] A possible way to experiment with discontinuous electrification could be to add a storage device on one train and ask the driver to drop and raise the pantograph to mimic OHL discontinuities. In comparison, it is possible for trackside energy storage applications to experiment with a real device, e.g. by adding a storage system next to a substation or TP Hut on dc.

Whilst it may be theoretically possible to build energy storage devices in the required sizes to achieve the main goal of driving trains through gaps, there is a need for an overall feasibility of the scheme. The initial investment must address the cost reduction of electrification, the additional cost of storage devices, cost of retrofitting exiting trains if applicable, development cost and approvals cost. The life cycle implications must address reliability, risks, safety, additional energy cost, emission cost (CO_2), environment impact, additional maintenance required, equipment replacement cost over the lifetime, cost of disruptions to the service which may be caused by stranded trains, failures, incompatibility of trains, sustainability, recyclability, routine and emergency maintenance, etc.

As the main objective in this work is to determine the feasibility of discontinuous and discrete electrification the technical assessment and economic impacts must be evaluated carefully. Discontinuous and discrete electrification combined with onboard energy storage devices will generate various technical problems, cost implications, advantages and disadvantages that must be identified and estimated in detail. Should these schemes be considered for implementation there will clearly be requirements for a multi-disciplinary approach involving different parties.

Because of the large instantaneous power capability, super capacitors are a preferred option to recover braking energy, particularly on dc. There have been many successful applications in this area in both trackside and train onboard dc line applications. Super capacitors exhibit high power capability for short durations, and accordingly the size and cost can be optimised to fulfil the requirements. In comparison, a self powered train through a short gap requires a finite level of energy that must be available. The size of the super capacitor could be minimised by running the train at reduced performance when operating through a gap to minimise the energy requirement. Unlike the case for recovering braking energy, where the instantaneous power peaks must be met, there is no need to maximise the power when operating through a gap. As such, super capacitors may be the preferred option for discontinuous electrification with short gaps.

For discrete electrification there is a need for a relatively large stored energy. Hence, the best and only choice is batteries. Batteries have considerably larger energy storage capability compared with any other energy storage devices. Generally, for longer useful life of the battery the normal operating ratio between the usable energy and stored energy, quantified by the DOD, should be maintained at low levels. In some applications the DOD is 10%, or even lower. This compares to 75% in super capacitors and flywheels.

If the battery is designed to have relatively low DOD there is a possibility that in emergencies it can be operated at larger DOD. This is an important feature, should there be demand for energy beyond the preset level. This characteristic will provide a safety buffer against scenarios such as trains being stranded in a gap during unplanned events. Generally, the available energy from a battery based on the DOD design can be increased substantially during emergencies.

The energy capability of batteries is orders of magnitudes larger than super capacitors and flywheels, but batteries have lower power capability. Batteries can be designed within specific range of power and energy densities, and normally low power large energy density batteries are cheaper than large power low energy density batteries.

In general, for short gaps in the order of a few hundred metres and with suburban, regional or intercity trains super capacitors, or flywheels, would be more suitable than batteries for frequent cycling. The energy demand in these scenarios is relatively small. Batteries may also be used in these applications, delivering reduced power and consequently reduced performance, but possibly used in emergencies only.

For freight applications, and for gaps larger than 500m, and up to a few kilometres, batteries are the preferred option since super capacitors or flywheels would be incapable of delivering the required level of energy.

For there to be an optimum utilisation of the storage device, generally, both the power and energy capacities must be used to the full. This is a key design criterion in all these applications to optimise the size of energy storage system.

3 Hybridisation of Electric Vehicles

3.1 Interface Requirements

Electric hybridisation usually classified as parallel hybridisation. The storage device is connected to the dc link in modern electronic drives trains as shown in Figure 3. The total summation of power at the dc busbar must equal zero at any moment in time. The efficiency between the dc link and output traction power can be defined as, $P_m/V_{dc}I_{dc}$, and the overall efficiency defined between the wire to wheel is $P_m/VI\cos(\theta)$ (see Figure 4).

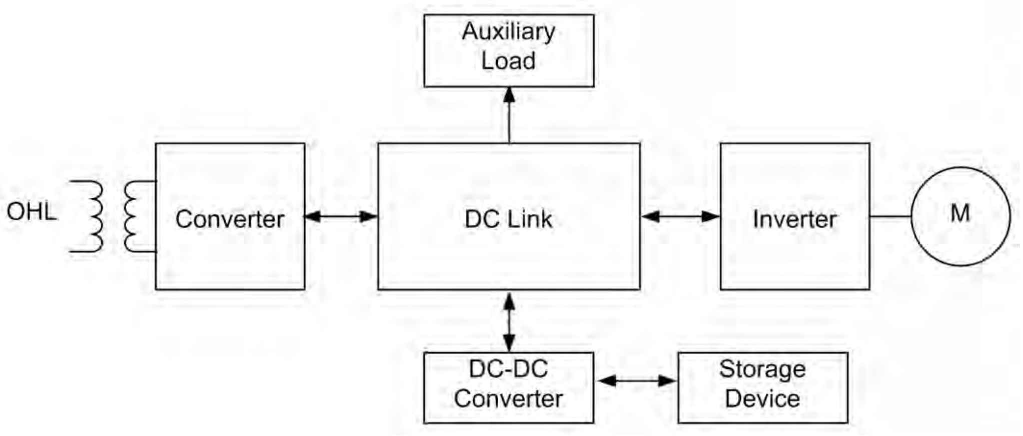

Figure 3 - Energy balance in a hybridised electric vehicle

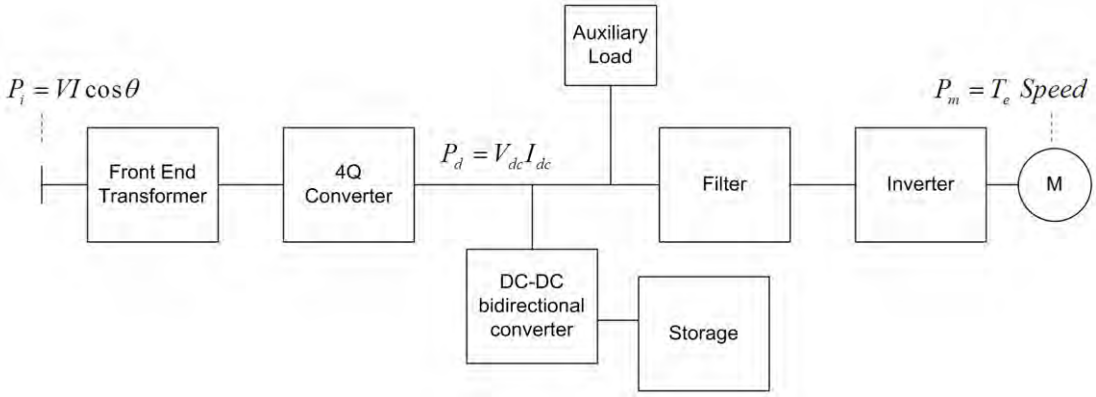

Figure 4 - Block diagram of a hybridised electric vehicle

Batteries and super capacitors can be integrated with the traction package using a bi-directional dc-dc wide range power converter as shown in Figure 4. The dc link typically varies between 800Vdc and 1500Vdc depending on the train type, rated power and design of the inverter. Modern ac drives employ SVM switching techniques instead, or in addition to, PWM enabling the dc link voltage to vary within preset limits.

Battery and super capacitor systems usually designed to operate at much lower voltages. In case of super capacitors, as the stored energy is proportional to the square of voltage, the terminal voltage must be dropped considerably to release most of the stored energy. Typically the voltage of a super capacitor is controlled to halve the maximum level giving a usable energy of 75%. Batteries on the other hand maintain the terminal voltage to within specific limits even most of the energy is released. The useful life of a battery is lengthened by minimising the DOD, and for the longest possible life, the DOD must be maintained at levels possibly below 10%.

The simplest method to control the energy of a battery or super capacitor is to use the circuit shown in Figure 5. The largest component in this circuit is the inductor. During charging Q2 is switched off and Q1 is PWM regulated. During discharge Q1 is maintained off, and Q2 switching is PWM controlled to maintain sufficient current in the inductor to raise the output voltage. At low voltage levels, and in both cases of charging and discharging, large currents need to be passed through the inductor resulting in poorer efficiencies.

There are other methods to build a bi-directional dc-dc wide range converter. In case the common points between the two sides need to be isolated, a high frequency transformer incorporating an inverter and rectifier sets on both sides, can be used. Such a converter would be more expensive and more complicated to control.

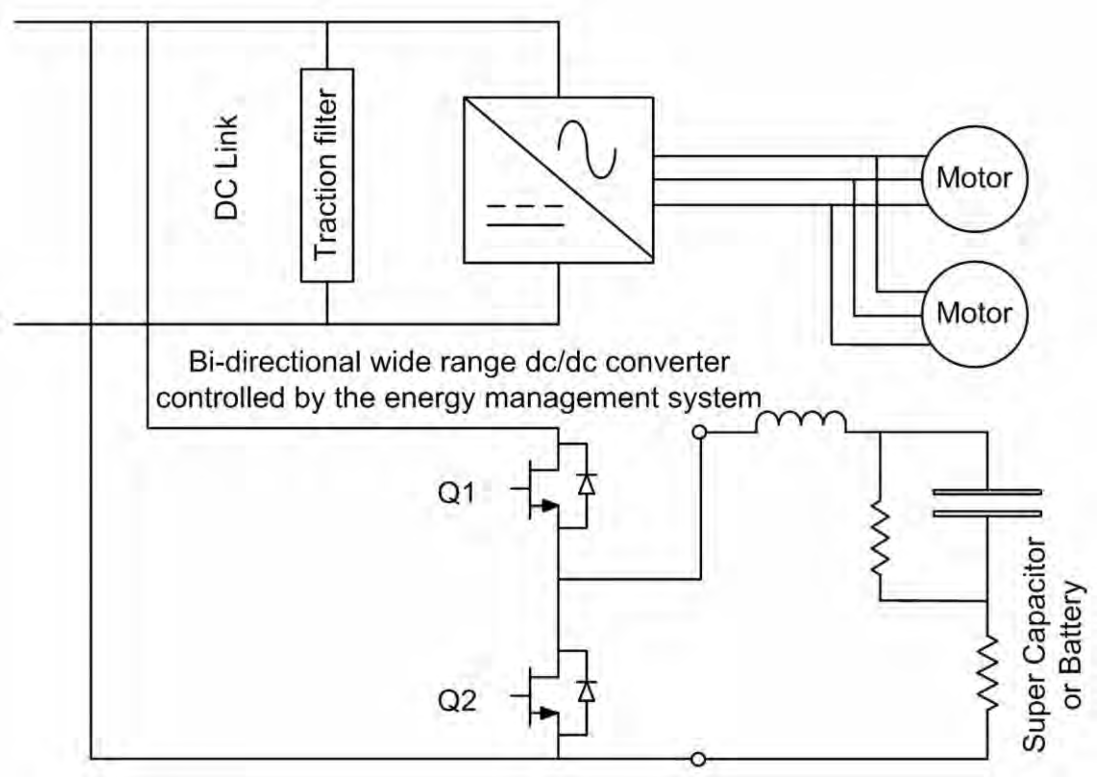
DC Link
Traction filter
Motor
Motor
Bi-directional wide range dc/dc converter controlled by the energy management system
Q1
Q2
Super Capacitor or Battery

Figure 5 - Interfacing a battery or super capacitor storage system in modern ac drives train

For the MLC flywheel technology case the magnetic circuit of the rotor is integrated within the carbon fibre flywheel. This makes the interface relatively simpler. The interface can be achieved by inverter which operates in similar fashion to that of the traction inverter. It must be capable of transferring power in both directions, between the dc link and the rotating plant (see Figure 6).

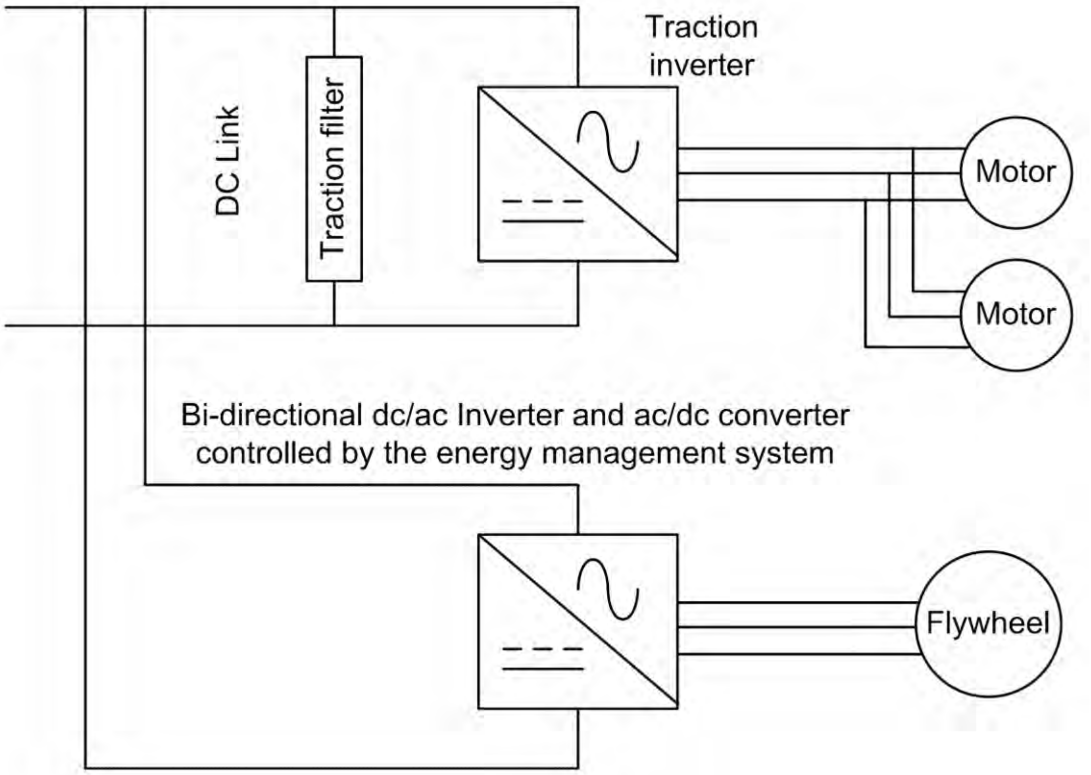
Traction inverter
DC Link
Traction filter
Motor
Motor
Bi-directional dc/ac Inverter and ac/dc converter controlled by the energy management system
Flywheel

Figure 6 - Interfacing a flywheel storage system in modern ac drives train

3.2 Retrospective Integration Requirements

If the storage device is to be integrated onto an existing train the interface requirements need to be identified. The following establishes some principles:

- The front end pulse converters on existing trains are likely to feature dc link feedback, dc link voltage and current for control of the duty and phase for the front end converter. Also, the inverters are likely to feature dc link feed forward (in particular current). Therefore it is desirable the dc link voltage is maintained within the existing limits. It is realised this may not always be practicable, and for efficiency reasons lowering of the min allowable dc link voltage may be desirable.
- Some train traction inverters are also likely to feature dc link feed forward to predict power flow. This will need to be examined on a train by train basis.

- It is considered the driver should have control of any emergency situation should the storage used for emergency only. Delivery of emergency power from the storage system could bypass some of the train systems. This should be seen as a normal, but only occasional event.
- The dc link current and voltage limits need to be determined. For many trains these will be set as control parameters within the controller software.
- The load presented to the new converter needs to be considered. Presently it is thought the current would be injected downstream of the front end filters on the dc link and upstream of the capacitors. This needs to be considered for each train type so the implications can be understood.
- A specific feature of this application is the sensitively of the converter output upon supply (in this case the storage medium) and the dependency of converter output upon the load - both need to be considered. The converter must be controllable over the whole operating range. This may present a challenge for some topologies.
- When the train is disconnected from OHL the dc link volts will be held up by the dc link capacitors for a few seconds but will then collapse. In automatic energy management control the energy storage system is expected to maintain the dc link at minimum volts and deliver the current requirement of the loaded induction motors.
- The storage system converter controller requirements need to be carefully thought out. The strategy could be based upon detection of falling dc link volts and a demand signal (in case of manual operation emergency driver push button may be used). The control philosophy should initially be based upon the converter having no dynamic effect i.e. it should not under normal circumstances be able to affect the dc link voltage level, unless there is a pending demand that is the link voltage should only be held up if necessary. Any requirement for regulation of traction supply (eg in the dc train case) under normal operation will have significant impact upon the safety case.

These are areas that in practice will require on track trials to be undertaken. More work is required to consider the strategies for ac and dc control.

3.3 Train Types

Four different types of trains are considered in the investigation, these are;

- Suburban: the train characteristics are based on 4-car class 317, or 4-car class 365/465, with full passenger load. The train resistance is provided for open section and tunnel sections.
- Regional: the train characteristics are based on 8-car class 317, or class 365/465, with full passenger load. The train resistance for open and tunnel sections is assumed to be twice as that for suburban.
- Intercity: the train characteristics are based on 9-cars + Class 91 locomotive, or 9-car Class 390 pendelino, with full passenger load.
- Freight: the train is based on class 6 characteristics[3] with full load of 1,724 tonnes. It operates at constant power above 30 kph with maximum speed of 100 kph.

In all cases the efficiency (shown in section 10) is defined between the dc link and the output mechanical power. Also the train resistance from standstill have been included, which is not accounted for in the Davis coefficients.

The terms 'Suburban ', 'Regional ', 'Intercity ' and 'Freight ' are used for these train types throughout this document.

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[3] Rule book, TW1, section 2, page 16, max speed 60 mph.

4 Coasting and Discontinuous Electrification

A discontinuous electrification scheme is a scheme where gaps of a few hundreds of metres in length (maximum 500m) are introduced in the OHL. There are three operating scenarios to be considered, coasting through the gap, cruising at constant speed and start from standstill within the gap. These scenarios are described in the following three sections.

4.1 Coasting Through Short Gaps

With short gaps, if the trains can rely on coasting alone then clearly there will be no need for onboard storage devices. One way to achieve this may be to integrate the train operation with the signalling system. This, however, is still inadequate to prevent trains stopping within a gap during emergencies, e.g. failures, trespassing etc. This section shows the relationship between speed, coasting distance and gradient.

The coasting distance a train can travel is proportional to the ratio of its mass divided by the train resistance. As such heavy train with small train resistance will travel longest distance, and the opposite, light train with high train resistance will travel shortest distance under coasting.

For the four train types assumed in section 3.3, as the train resistance to train mass ratio is assumed constant for all trains (artificially maintained by adjusting the train resistance), the deceleration rate and consequently the travelled distance under coasting are nearly the same for all four train types considered (see Figure 7).

To be able to achieve a minimum exit speed of, say, 16 kph (10 mph) the train must be operating at a specified minimum initial speed at the moment of entering the gap. Figure 7 shows indicative minimum entry speeds for different gap lengths on a flat and 1.25% gradient track for the four train types considered.

The characteristics of suburban, regional, intercity and freight trains are shown in section 10. The train resistance is assumed to be for tunnel sections. As expected all of the trains exhibit the same performance because the ratio of train mass to train resistance is maintained approximately the same for all types.

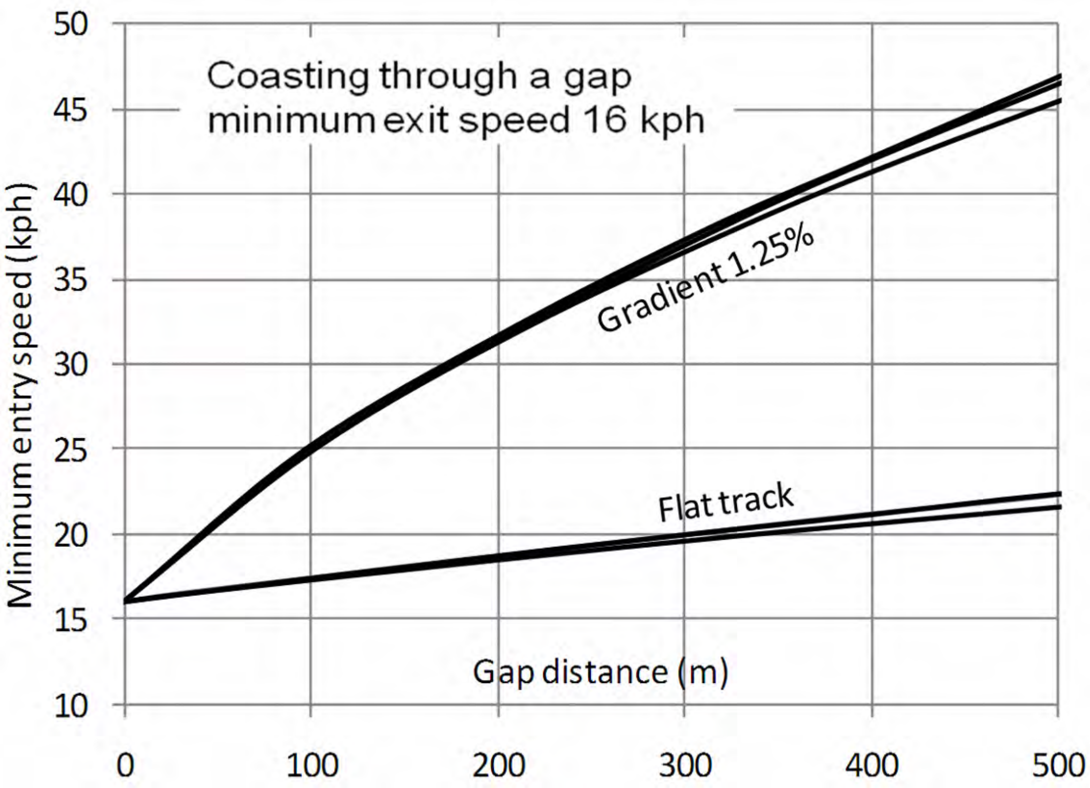

Figure 7 - Minimum initial speed to coast through a gap to achieve 16 kph exit speed

4.2 Constant Speed Operation

At constant speed the acceleration force is zero and both the train resistance and gradient force are constant (refer to section 12.2). Consequently the power required to maintain constant speed is also constant. As such, the power demand increases with speed. For energy, as the train resistance increases with speed, the amount of energy required to move the train for the same distance increases with speed. This is generally true except at low speeds where the aerodynamic resistance becomes small compared with the rolling resistance, in particular the initial resistance from standstill. If the speed is reduced, and if combined with the track gradient, there is a specific speed range where the energy demand starts increasing at low speeds (see Freights in Figure 8).

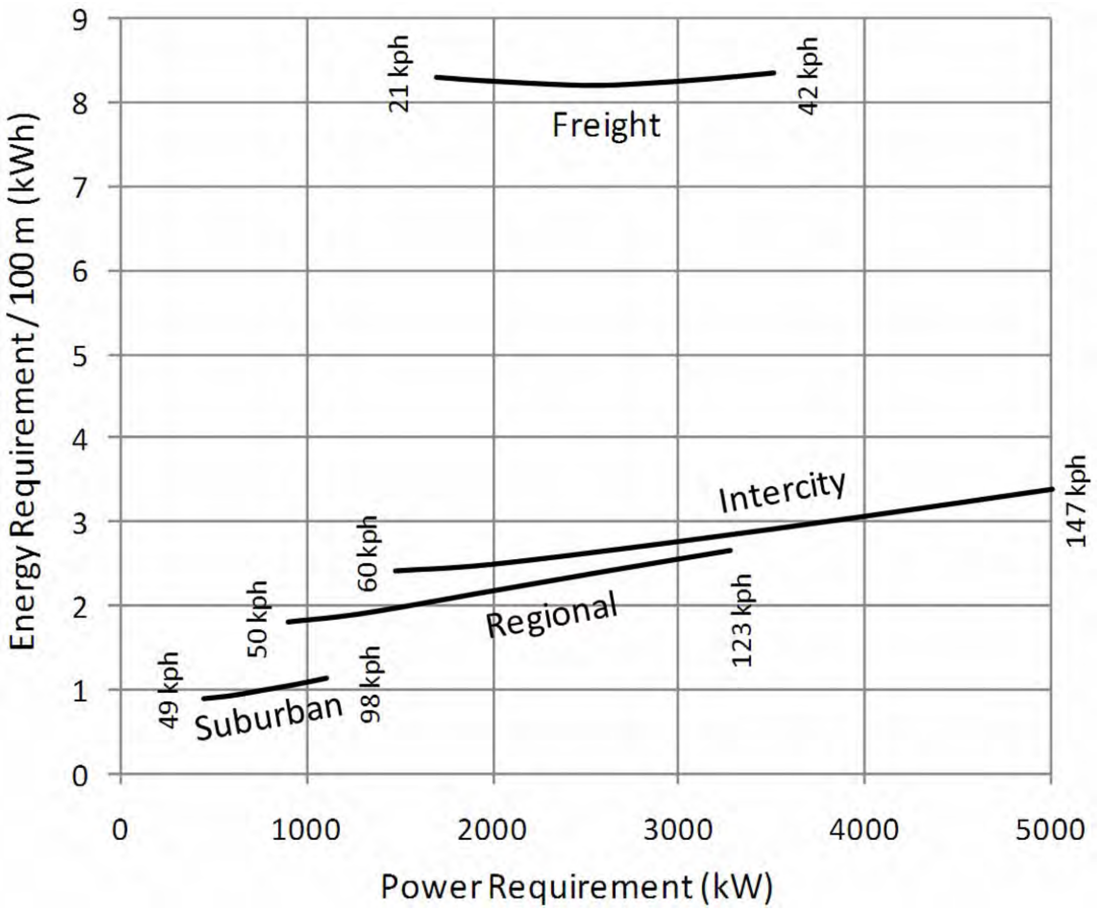

Figure 8 - Power and energy requirement for different trains operating at constant speed operating in a tunnel section at 1.25% gradient

Figure 8 shows the energy demands to operate different trains for 100 metres at constant speeds. The maximum speeds shown are the maximum limits that different trains can achieve. For the lower end of speeds, these have been arbitrary chosen.

4.3 Operating from Standstill

When a train starts from standstill at full power, the relationships between energy consumed, speed, time and distance for the four train types considered is shown in Figure 9. The track gradient in these calculations is assumed 1.25% and the train resistance is for a tunnel section.

Comparing a regional train with suburban, the energy consumed is twice to travel 500m distance from standstill. It does that in 48 seconds compared with 56 seconds for a suburban train. An intercity train would take 79 seconds but consumes slightly less energy than a regional train for the same distance. A freight train would, obviously, take longer time and much more energy to move the same distance.

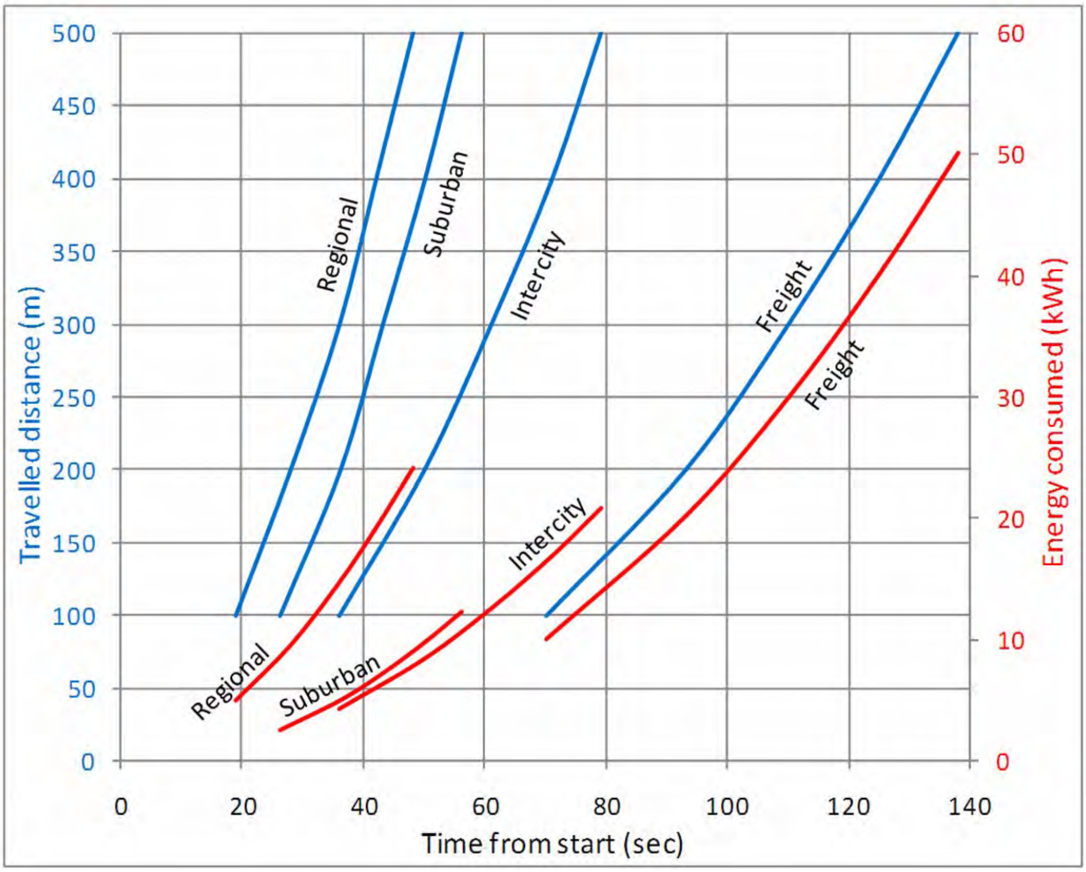

Figure 9 - Energy, time and distance relationships when starting from standstill at full performance for different trains on a track gradient of 1.25% and in tunnel section

The energy requirements can be minimised by reducing the train performance at the expense of the total time required to move through the gap. This criterion is used to minimise the size of the energy storage device (see section 4.5).

4.4 Matching Storage to Demand at Constant Speed

4.4.1 Batteries and Super Capacitors

The Ragon plots of different energy storage devices, shown in Figure 1 and Figure 2, can be converted into absolute levels of available power and energy by specifying the mass of the storage device. These levels can be compared with the levels of power and energy demands shown in Figure 8 required by different trains to run at constant speed, per unit distance. An example is given in Figure 10 where the levels of power and energy demands are compared for a 1.5 tonne worth of energy storage devices and trains to travel 220m. The 'black' lines are the same as that of Figure 8 for power and energy demands for 220m gap length, compared with the available power and energy in different storage devices derived from the Ragon plots of Figure 2, shown as 'red' lines.

In Figure 10 the assumed DOD (available energy/stored energy) for batteries is 15%, super capacitors and Nano technologies and flywheels 75%. The assumed allowance made for the ancillary circuitries, such as thermal monitoring, voltage balancing, cooling, etc. (not including the dc-dc converter) for batteries is 8%, super capacitors and Nano technologies 10% and flywheels 4%. The discharging efficiency is assumed constant (note the efficiency is load dependent) at 94% for batteries, 95% for super capacitors, 98% for flywheels and 90% for Nano technologies.

To fulfil the traction requirements for a given train, i.e. black lines in Figure 10, the choice of a storage device, red lines, must be such that (a) the energy level is larger and (b) the power level must be at least at some intermediate level of the traction demand. For example, if we consider a 'Suburban' train in Figure 10 the traction demand can be met by 'S_Cap1' storage device.

Other devices also can meet the demand, such as the two types of batteries, flywheel or Nano. However, using an 'S_Cap2' device, whilst it meets the energy demand it has excessive power capability that is not required. On the other hand other devices, such as batteries, these devices can meet the power demand but would have considerable energy stored that is hardly used.

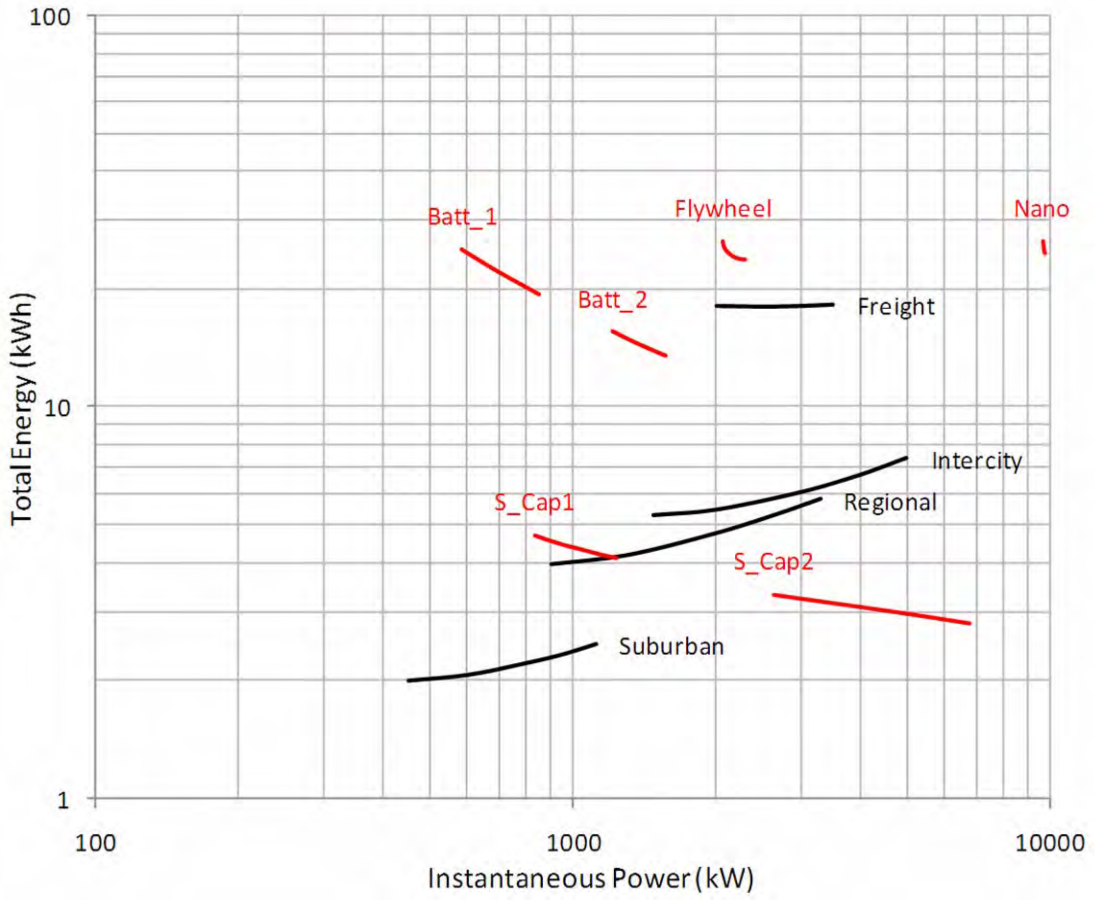

Figure 10 - Available power and energy against train demand for 1.5 tonne storage (excluding the dc-dc converter) for a 220 m gap length.

Note the dc-dc converter mass is not included in the figures quoted. The power and energy demands are for a gradient of 1.25% in a tunnel section.

To optimise the storage device for a given application, it is required to minimise its weight, and consequently its cost. There are two criteria to achieve this:

- The usable energy of the storage device must be larger than the total traction energy required by a margin of, say, 20%, and should not exceed 150%. This would ensure that no unnecessary penalty in terms of weight and cost is incurred.
- The instantaneous power capability of the storage device must be larger than the train power demand running at an

acceptable constant speed at maximum gradient. The acceptable speed is not necessarily the maximum speed.

In the example of Figure 10, if the weight of 'S_Cap1' is reduced to 1 tonne it would meet the two criteria above for a 'Suburban' train travelling through a 220m gap (see Figure 11).

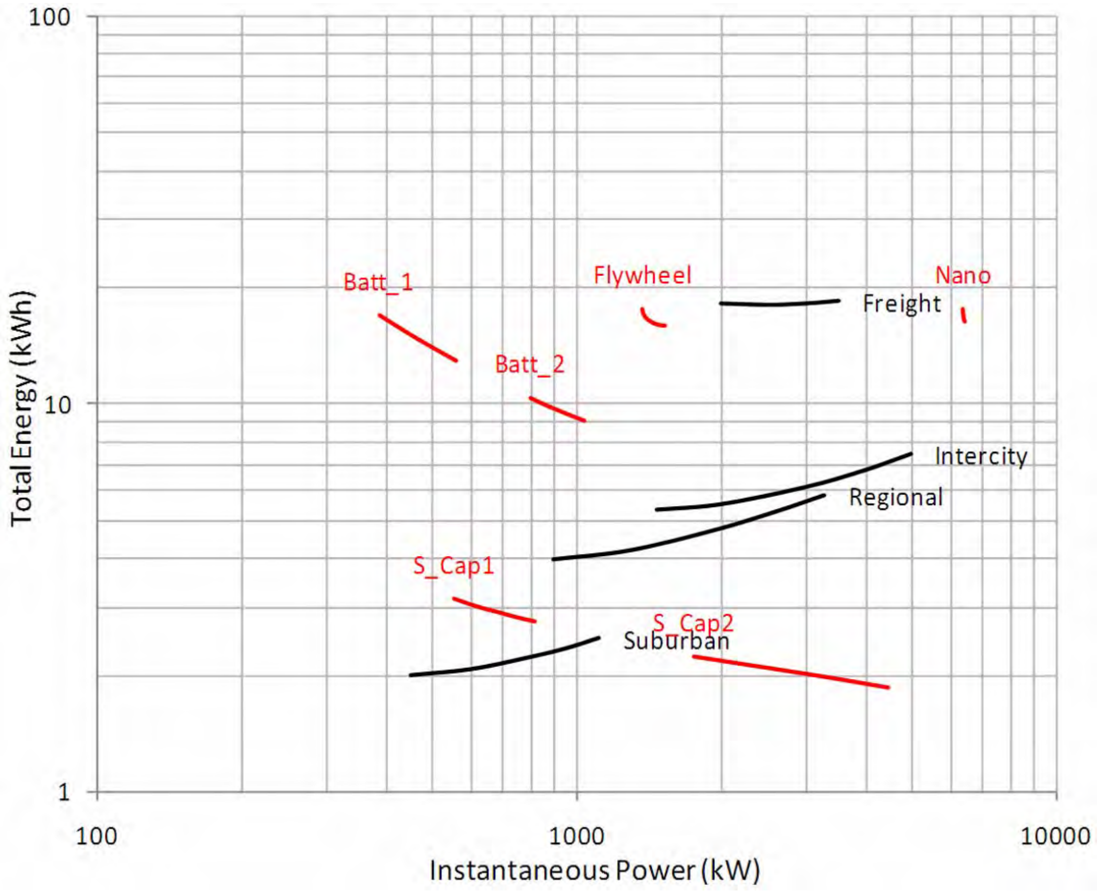

Figure 11 - Available power and energy against train demand for 1.0 tonne storage (excluding the dc-dc converter) for a 220 m gap length

This approach can be applied to sizing the storage devices for discontinuous electrification, where gaps are in 100s of metres, and discrete electrification, where gaps are a few kilometres.

Indicative results are presented in section 11 (Appendix: Indicative Storage Requirements). The storage mass in these results does not include the dc-dc converter. A more detailed model is also shown in section 7 and section 12 (Appendix: Model).

4.4.2 Nano and Flywheel Technologies

Figure 10 also shows indicative characteristics of Nano technology devices (super capacitors and batteries may also be referred to as Nano technologies). Such devices may be classified as either pseudo batteries or asymmetrical super capacitors. Prototype devices in this range have been demonstrated recently, but are not commercially available. The example given in Figure 10 is for a Jeol super capacitor which has relatively large ESR resulting in poor efficiency[4] compared with other known super capacitor devices. Clearly, the specific power and energy densities are much better compared with conventional super capacitor technology.

Other devices which are gaining ground are modern MLC flywheels. The characteristics shown in Figure 10 are based on a theoretical design for rail applications. This design is based on a racing car flywheel which was demonstrated successfully. This device exhibits larger specific power and energy densities compared with commercial super capacitors. The materials used in flywheels are conventional in nature and as such it is expected to be less expensive and would have better recyclability. The reliability of this device, however, is unknown. Also maintenance requirements would be very intensive.

The Nano and flywheel devices have been included in the analysis to provide a view for the future development and possible future improvements in energy storage devices.

4.5 Optimum Storage Size

Section 4.4 sets the requirements for storage devices, in terms of power and energy, to operate the trains at constant speed through a specified length of gap. It is also a requirement that the available energy must be sufficient to move the train through the entire gap length starting from standstill. This is a very important requirement as there is a risk of a train being stranded in the gap with no energy available in the storage device.

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[4] Jeol announced recently that they improved the ESR considerably, but information is not available. It is predicted that cost will be similar to normal super capacitors if demands increased beyond 200,000 units.

In all cases the specified energy to operate a train at constant speed through a gap will be insufficient and much smaller than energy required by the train to move from standstill through the entire gap length. This is because, the train must be accelerated at a finite rate which means an additional acceleration force will be required. The acceleration force is proportional to the train mass and as such heavier train will require more energy.

This means that the energy device needs to be sized to cope with the case of a 'start from standstill' scenario. In most cases the energy required to operate the train from standstill is orders of magnitudes compared with the constant speed operation demand. Consequently the energy storage requirements would increase by the same orders.

However, to keep the size of the storage device the same as that specified for the constant speed case the train can be operated at reduced performance when starts from standstill. The performance must be reduced to minimise the energy requirement to a level which is the same as that required for maximum constant speed operation.

The train performance, starting from standstill, can be reduced by introducing one or more of the following:

- Reducing the initial, or instantaneous, acceleration.
- Limiting the output power of the storage device.
- Imposing a maximum speed limit.

These measures can be embedded within the train controller as part of the energy management system. A simulation tool, ESSRA (see section 7 and Appendix section 12), provides a facility to determine the energy consumption when operating from standstill. By varying the three parameters shown above for a given train, and for a given gap length and gradient the energy demand can be adjusted to be the same as that for the constant speed case.

The simplest method, and most efficient that minimises energy demand is to limit the maximum speed. Figure 12 shows the required maximum speed limits for different trains, and variable gap lengths, on a flat and 1.25% gradient when starts from standstill. Imposing these speed limits when operating from standstill will result in energy demand levels that are of similar order for the case when the train is operating at maximum constant speed. The energy storage requirement can be reduced further by minimising the maximum permissible speed limits when starting from standstill.

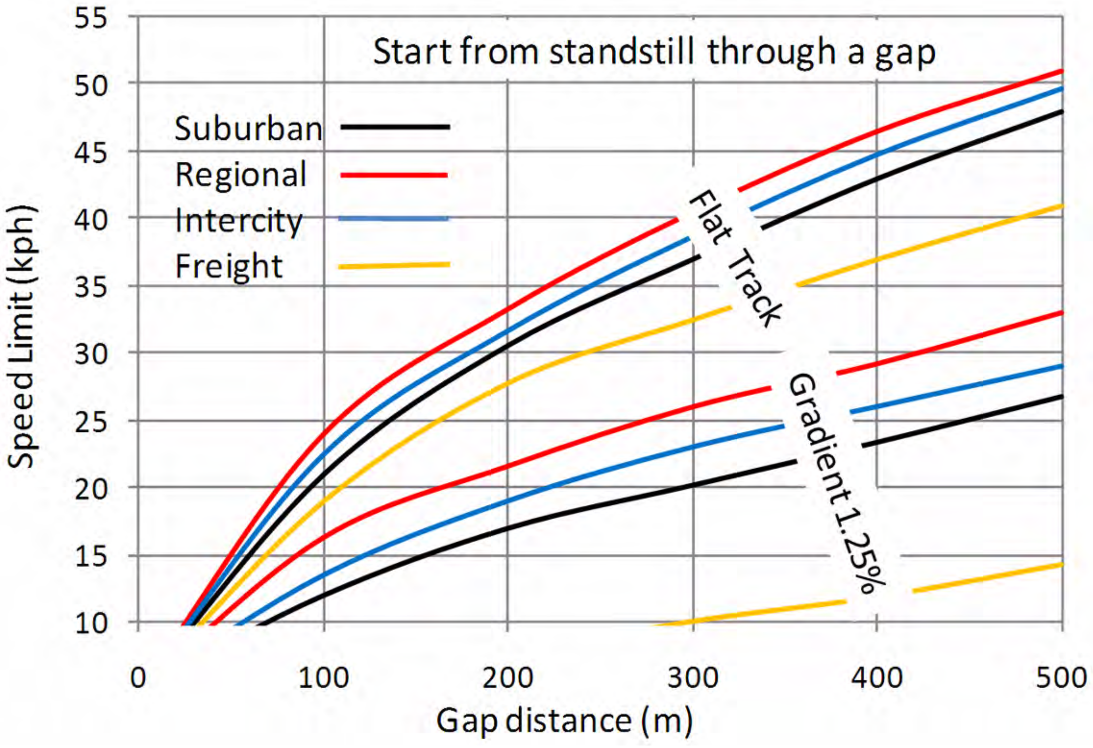

Figure 12 - Start for standstill at reduced performance

Note, in Figure 12 the storage device of a freight train, whilst capable of operating the train at constant speed through the gap, it would be inadequate of running the train against 1.25% gradient from standstill throughout the entire gap length. The reason is, simply, the train large mass requires higher acceleration force and consequently greater energy demand.

4.6 Types of Gaps

The term discontinuous electrification refers to OHL gaps in the order of a few hundred metres. Gaps in discontinuous electrification could be created by either the absence of the OHL (physical gap), or by means of a 'Neutral Section' type arrangement (electrical gap) incorporating an extended earthed contact section between the in-line insulators. The latter case allows the pantograph to remain raised throughout the gap, but operation must be maintained at limited speeds. More detail on this subject is given in T777 and T778 projects, References 3 and 4.

Physical gaps require an automatic detection system on the train, in particular when gaps are installed in large numbers. The detection point must be located at some distance before the gap to allow for the response time of pantograph dropping. This distance is dependent on maximum line speed, e.g. 450m distance for 160kph speed limit. However, it is possible that the control mechanism on the train may initiate pantograph dropping at shorter distances depending on the speed. A recommended scheme for the detection distance versus speed profile is suggested in Figure 13. Basically, the lower the train speed the shorter the distance (maintaining the same response time) for initiating pantograph dropping command. The reason for that is to minimise the durations of self powering the train under the gap, hence minimising energy storage requirement.

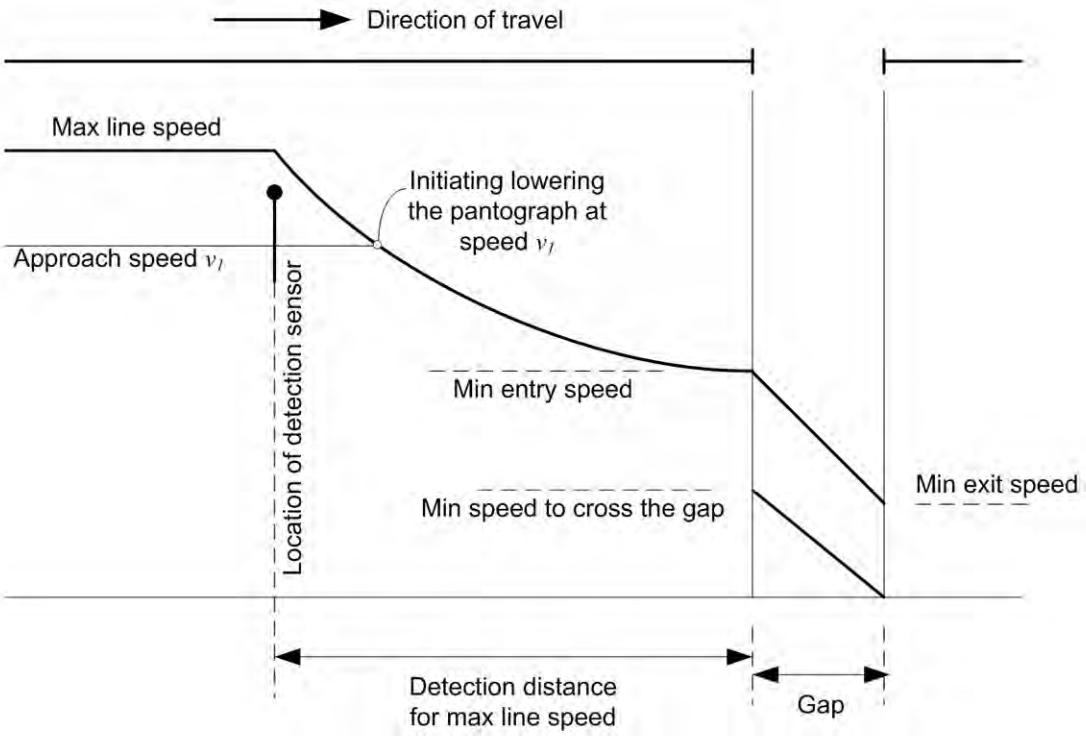
Direction of travel
Max line speed
Initiating lowering the pantograph at speed v_l
Approach speed v_l
Location of detection sensor
Min entry speed
Min speed to cross the gap
Min exit speed
Detection distance for max line speed
Gap

Figure 13 - Distances at which the pantograph lowering commands initiated

For a train to be able to coast through a gap, it must enter the gap at a minimum specified speed. This entry speed must be above certain level that ensures a satisfactory exit speed. Clearly, as long as this condition can be met all the time there will be no need for additional onboard storage. With a storage device, nonetheless, the energy can be used to uphold the train speed and maintain performance.

The main risk, however, is when the train is forced to stop within the gap, due to occasional adverse situations e.g. vandalism, trespass, etc. For such events the primary function of the storage device would be to power the train outside the gap. Given that the energy required in this scenario is larger than the case for maintaining constant speed, then a key parameter in the storage device design is to store sufficient energy for the 'start from standstill' scenario.

Therefore, the key design criterion of the storage device is to be capable of storing sufficient energy to move the train, starting from standstill, throughout the gap length.

4.7 Hybridisation Options

As discussed, a key parameter in determining the device rating is the minimum amount of energy required to move a train outside the gap starting from standstill. In addition, to determine the onboard storage device type, it is necessary to specify the charging and discharging pattern. It is a choice between (a) frequently charging and discharging cycling scheme. Such a scheme would also be suitable for capturing barking energy, or (b) using a storage device that stores energy for emergencies only. These two schemes are discussed in the next two sections.

4.7.1 Frequent Cycling

Frequent cycling of energy is required when gaps are introduced at stations and underneath bridges, or other structures, following station departures. In these cases relying on coasting is not possible. There are in addition scenarios where speeds are limited to very low levels in restricted areas where no OHL clearances available. There is also a case for onboard recuperation of braking energy utilising the frequent cycling scheme.

In such schemes super capacitors are a suitable choice due to the large cycling capability of charging and discharging and the large instantaneous power available. Table 4 and Table 5 show the minimum requirements for a super capacitor based energy storage system for a suburban (typical 4-car Class 365) and intercity equivalent (9-car Class 390) trains respectively.

Gap (m) @ gradient %	**Minimum super capacitor requirement for a suburban train (4-car Class 365)**					
	Mass (tonne)	**Minimum Energy (kWh)**	**Power Capacity (kW)**	**Volume (m^3)**	**Max Recovery Speed kph**	**Converter Mass (kg)**
100 @ 0%	0.4	1.09	220	0.993	15	44
300 @ 0%	0.6	1.59	350	1.43	15	70
500 @ 0%	1.0	2.1	700	2.17	15	140
100 @ 1%	0.7	1.83	400	1.67	15	80
300 @ 1%	1.35	3.7	720	3.41	15	144
500 @ 1%	2.05	5.63	1100	5.18	15	220

Table 4 - Minimum super capacitor energy storage requirement for frequent cycling of a Suburban train @ DOD 75%, figures are per train. Maximum speed from standstill is 15 kph.

Gap (m) @ gradient %	Minimum super capacitor requirement for a intercity train (9-car Class 390)					
	Mass (tonne)	Minimum Energy (kWh)	Power Capacity (kW)	Volume (m^3)	Max Recovery Speed kph	Converter Mass (kg)
100 @ 0%	1.15	3.13	650	2.8	15	130
300 @ 0%	1.4	3.8	800	3.39	15	160
500 @ 0%	1.7	4.7	900	4.31	15	180
100 @ 1%	1.9	5.46	1000	4.84	15	200
300 @ 1%	3.9	10.3	2200	9.53	15	440
500 @ 1%	5.4	15.08	3000	13.3	15	600

Table 5 - Minimum super capacitor energy storage requirement for frequent cycling of an Intercity train @ DOD 75%, figures are per train. Maximum speed from standstill is 15 kph.

4.7.2 Emergency Storage Device

Discontinuous electrification may be designed to be heavily reliant on trains being coasting through gaps, rather than self powered. To overcome the problem of stranded trains within a gap, there is a scope for designing a relatively small storage device capable of powering the train during emergencies only. The energy stored in such a device must be sufficient to move the train at low speeds from standstill through the entire gap length.

The ideal choice for such a device is battery. It is known that battery life is shortened by deep discharging and frequently large discharging current rates. Both of these features are required in this application. However, using the battery in this fashion will only be required during emergencies. Such emergency events may take place a few times during the lifetime of a train, and it may never happen at all. As such, the battery could be designed to completely discharge its energy for limited number of cycles. This would result in much smaller battery size requirements and consequently lower cost.

The scheme would be viable if train operations rely primarily on coasting through gaps in a discontinuous electrification scheme. The system would require an integrated design approach that incorporates the layout and locations of the gaps, signalling system design, timetabling design and operation. The storage device will only be used for emergencies during unscheduled events where a train stops within a gap.

Table 6 and Table 7 show indicative lithium ion battery sizes for suburban and intercity trains respectively. The minimum battery sizes are limited by the power requirements. This is reflected in the fact that the DOD specified is still relatively small. This suggests that these batteries are capable of supporting the trains for even longer distances than the 500m considered.

Gap (m) @ Gradient %	Minimum Lithium ion battery requirement for a suburban train (4-car Class 365)						
	Mass (tonne)	@ DOD (%)	Energy (kWh)	Max Power (kW)	Volume (m^3)	Exit Speed (kph)	Converter Mass (kg)
500 @ 0%	0.20	40	4.33	180	0.08	33	36
500 @ 1%	0.36	39	7.28	325	0.14	31	65

Table 6 - Minimum lithium ion energy storage requirement for a suburban train, figures are per train

Gap (m) @ Gradient %	Minimum Lithium ion battery requirement for an intercity train (9-car Class 390)						
	Mass (tonne)	@ DOD (%)	Energy (kWh)	Max Power (kW)	Volume (m^3)	Exit Speed (kph)	Converter Mass (kg)
500 @ 0%	0.30	54	8.51	270	0.117	28	54
500 @ 1%	1.22	35	22	1100	0.475	38	220

Table 7 - Minimum lithium ion energy storage requirement for an intercity train, figures are per train

The energy storage requirements stated in Table 6 and Table 7 are comparable with the sizes of typical EMU auxiliary batteries. Such batteries are usually rated at 80-100 Ah at 96V terminal voltage[5]. Clearly, there is a scope to design a battery that would serve both purposes, for supplying the auxiliary load and providing emergency traction energy. The only issue is the instantaneous power rating capability of the battery required for traction. This should not be a problem if modern batteries, such as lithium ion, are used.

The battery sizes could be reduced further if the power capabilities of the batteries improve. With a 40% DOD, and if the specific power of the battery is doubled, it would be possible to half the size of the battery by designing for 80% DOD. New generations of lithium ion batteries coming in the market promise larger specific power, e.g. the new Hitachi traction batteries. As such, this scheme would be more attractive with these batteries. Furthermore, as the battery is hardly in use throughout its life, the maintenance requirements will be significantly reduced leading to further reduction in running costs.

4.7.3 Combined Energy - Power Storage Device

Super capacitors in combination with batteries are common architecture in many applications that utilise the energy storage capability of the battery and provides the ability to deliver peak power using the super capacitor. In such a scheme it is required that two separate bi-directional variable dc-dc converters to be provided.

Although, some successful trials of combining super capacitors and lead acid batteries in hybrid applications were demonstrated, in our application this option is not very attractive. Using two storage devices having different terminal characteristics would require the use of separate controllers leading to further complications, larger weight and higher cost.

The advent of high specific power batteries, such as the new generation of lithium ion batteries, would pave the way of providing the required characteristics for energy and power simultaneously, in particular if the battery used for emergency applications as described in section 4.7.2.

4.8 Energy Management System

The main task of the energy management control system is to determine when to store energy and when to release it, and at what level. In principle when the line voltage is available it means the train is operating from the supply, and when the line voltage

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5 For DMUs the auxiliary battery is 24V and a separate starting battery is in use.

collapses the vehicle may be powered by the storage device. If the process of moving through a gap is automated by a detection signal, and a track to train communication, then the detection signal can be used to change the mode of operation.

Furthermore, the controller must allow for two modes of operation, normal mode, e.g. cruising at constant speed, and emergency mode for the 'start from standstill' scenario, in which case manual activation may be used. The storage device can also be used to recover braking energy or providing power during peak demands.

The control strategies are altered with the mode of operation, and for each mode there could be a number of strategies. Below are four strategies that can be implemented in normal mode (see section 12 for detail).

In all these strategies there are general rules that should be obeyed and performed continuously in real time, these are:

- The storage device is charged up at maximum rate during regenerative braking when operating under the wire or within a gap.
- Maximum discharging rate is permitted when motoring within a gap.
- Under the wire the storage device is continuously regulated to achieve a variety of functions.

When operating under the wire there are several energy management strategies need to be considered as described below:

1. A control strategy that maintains maximum stored charge all the time. This strategy is desirable when powering the train through gaps is the prime and only function required.
2. A control strategy that maintains minimum charge all the time. This strategy is desirable when the main function is recovering maximum braking energy.
3. A control strategy where the energy stored is dynamically regulated by the speed. This strategy is suitable for both, operating through gaps and recovering braking energy. The controller minimises the energy stored at high speeds to enable capturing maximum regenerative braking. On the other hand, the energy stored is maximised at low speeds

to enable powering the train through a gap should it be required.

4 A control strategy based on a 'Look Ahead' algorithm. This strategy is route dependent. The technique is based on incorporating the route details within the control strategy of the storage device. This will enable anticipating motoring or braking requirements ahead, hence its name.

The last technique could be relatively simple. For example, the controller maintains maximum energy if there is a gap ahead, or maintaining minimum energy when braking is expected. Therefore, operating with both gaps and recuperating braking energy can be accommodated for relatively easily using this controller.

Train onboard controllers are increasingly being introduced recently. Examples include operation optimisation, eco-driving, regulation, traffic management, tilting locations (if exist), etc. Integrating a storage device controller strategy would be a relatively easy task using this technology.

5 Case Study

The case study presented in this section attempts to assess discontinuous electrification schemes using super capacitors as the main storage devices. The assumptions made are in general terms. The investigation covers costs of the storage devices against savings in electrification at the introduction of discontinuous schemes. The technical aspects associated with introducing storage devices on the railway have also been addressed.

Although the study focuses on super capacitors, other schemes such the use of batteries in discontinuous or discrete electrifications, can also be assessed in the same fashion and using the same principles. Clearly, a more detailed and route specific assessment will be required should a discontinuous electrification scheme is considered for implementation.

New technologies often prove expensive in the beginning due to high development costs. However, the overall system costs will be considerably reduced when the new systems produced at commercial scale.

The cost evaluation of storage devices requires the use of functions that comprise two terms: fixed cost and variable costs. Both of these costs must be assessed over the lifecycle of the product. The analysis focuses purely on cost comparisons. However, other factors, eg the social impact, are clearly equally important and should also be considered if this scheme is implemented.

The fixed cost includes all costs associated with the storage devices minus the expected reduction in electrification investment. The fixed costs include:

- Cost reduction in electrification investment (savings).
- Cost of storage devices which includes,
  - Cost of cells, not applicable to flywheels
  - Cost of packaging and monitoring units
  - Cost of dc-dc power converter (or ac-dc for flywheels)
  - Development cost
  - Approvals and acceptance cost
  - Cost of retrofit, if applied to existing trains
  - Installation cost on new trains
  - Cost of automatic detection of gaps installed on the train

The major part of the variable costs is maintenance cost and equipment replacement cost. These can be summarised as follows:

- Maintenance
- Equipment replacement
- Additional cost functions, including:
    - Increased energy cost
    - Emission cost (CO_2) and environment impact
    - Cost of passenger seats lost to the storage device
    - Increased insurance premium
    - Safety
    - Reliability
    - Operating risks, eg cost of disturbances caused by stranded trains
    - Compatibility of trains
    - Sustainability
    - Recyclability

The presented analysis attempts to determine indicative figures for a discontinuous electrification scheme example with various cost factors and their contribution over a lifetime cycle. For this purpose many assumptions, and extrapolations, have been made that are based on best estimates and engineering judgment. These assumptions are stated in the relevant sections that will follow, and should be treated as indicative.

The example considered is for a discontinuous electrification scheme which is assumed to be 100 mile long employing 32 gaps at an average gap length of 300 metres, giving an average distance between gaps of 3 miles. The storage devices considered are super capacitors and used on suburban, regional and intercity trains. No freight trains are assumed. The initial costs are addressed in section 5.1, variable costs in section 5.2 and section 5.3 addresses the Cost Benefit Analysis (CBA).

5.1 Fixed Costs

5.1.1 Cost Reduction in Electrification Investment

The reduction in initial cost of electrification, as a result of introducing gaps, will be treated in the cost benefit analysis as negative investment, having a negative sign. It is then possible to offset against this negative cost the fixed costs of the storage devices plus the variable costs over lifetime of the system. This approach would enable using the cost of saving in electrification rather than the total initial cost. A hypothetical example based on relatively optimistic assumptions is assumed and used for demonstration purposes. The presented figures must be treated with this fact in mind.

The example given in Table 8 assumes that 70% of the cost is required to electrify 94% of a 100 mile line. The remaining 6% (6 miles) represents the total length of gaps. At an average gap length of 300 metres there are some 32 gaps distributed over the 100 miles long line, i.e., at an average distance between gaps of around 3 miles.

Type of Infrastructures	Percentage of Cost	Percentage of Total Distance	Absolute Cost Proportion (£M)	Cost per mile £M/mile
A	70	94	140	1.48
B	20	5	40	8
C	10	1	20	20
	100%	100%	60 £M saving	

Table 8 - Hypothetical cost proportions of different types of infrastructures of an assumed electrification scheme, where (A) is simple double track straight runs: (B) crossing, change overs, points, stations, sidings, level crossing, etc., and (C) raising bridges, tunnels widening, route diversions, etc.

An acceptable, ball park, figure to electrify double track line is two million pounds per mile. This cost includes all civil engineering works such as raising bridges, strengthening of structures, etc. (a figure of £0.6 to £0.7 million per km per track has been reported). As such the total cost of normal electrification for a 100-mile line would be around 200 million pounds. For further details on the cost of electrification, refer to T633 research project (see Reference 5).

With 300 metre gaps discontinuous electrification the cost reduction is assumed £60 millions as shown in Table 8.

It must be emphasised here that the £60M saving is a pure assumption based on 30% reduction in cost of electrification by introducing gaps. This assumption must be used for demonstration purposes. In reality accurate cost estimates for normal and gapped OHL must be determined in detail and compared to establish a valid cost saving figure. In our example, for now, let us assume this figure £60M.

As there are many gaps, at relatively short distances between each other, it is conceived that driving through these gaps would involve an automated control of the train pantograph. This would require a system that involves a track to train transmission at the starting location (and possibly at the end) of every gap. Signal transmission equipments must be installed at all gaps, and every train must be fitted with detection equipments. Description of such a system is outside the scope of this study (refer to T778 and T777 projects for further details, References 3 and 4).

For the purpose of this study it is assumed that the additional infrastructures cost of such a system is embedded within the cost reduction of electrification. For trains, the cost is assumed fixed and added to the cost of the storage device.

5.1.2 Cost of Additional Equipments

For simplicity super capacitor devices are considered only in the analysis. Batteries, and other storage devices, can be assessed using the same approach. For flywheels it is perceived that the materials cost is much lower than that of batteries or super capacitors, but the major initial cost would be on development, and it would require substantial maintenance cost. Flywheels are not considered in this study as there are many uncertainties at this stage.

Costs are quoted in pounds assuming the current exchange rate against the € and USD[6]. Note here that due to financial market volatilities medium or long term predications are very difficult to estimate.

The cost components considered are:

C_s	Cost of cells
C_p	Cost of packaging and monitoring units
C_c	Cost of dc-dc converter
C_r	Cost of retrofit, if applied to existing trains
C_i	Installation and testing cost on new trains
G_g	Cost of automatic detection of gaps installed on the train

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[6] At the time of completing this report the £ has lost considerable ground against both the € and USD. There are also further uncertainties in the economy.

The cost of a super capacitor storage device is the sum of costs of the unit cells, C_s , packaging and monitoring units, C_p , and dc-dc power converter C_c.

$Storage\ Cost = C_s + C_p + C_c$

Cost of cells C_s

The cost of the cells unit, C_s , is proportional to the amount of energy stored, or if a manufacturer's quotation is given, by the number of cells, as follows.

$C_s = CellCost\ (£/kWh)\ x\ Energy = CellCost\ (£/cell)\ x\ N$, *where* N *is the number of cells*

In the case of very large orders, of more than 10.000 cells, a price reduction of 25% can be assumed. Indicative figures (recent) for Maxwell super capacitors are shown in Table 9.

Maxwell	Weight (g)	C (F)	Voltage (V)	Wh/kg	Cost in £	
					< 9 cells	> 50 cells
BCAP0650	200	650	2.7	3.29	~ 28.33	~ 24.03
BCAP1200	300	1200	2.7	4.05	~ 36.91	~ 36.05
BCAP1500	320	1500	2.7	4.75	~ 48.07	~ 42.06
BCAP2000	400	2000	2.7	5.06	~ 60.94	~ 54.08
BCAP3000	550	3000	2.7	5.52	~ 68.67	~ 60.94

Table 9 - Maxwell super capacitors cells specifications

Based on Maxwell super capacitor prices the cell cost for large scale orders, with 25% expected discount for large orders, would be around £16/Wh.

Cost of packaging and monitoring units C_p

The cost of packaging and monitoring units, C_p , can be assumed to be 30% of the cost of the unit cells, C_s .

$C_p = 0.3\ x\ C_s$

Cost of dc-dc converter C_c

The cost of the power converter is proportional to the power rating,

$C_c = \mathrm{ConverterCost}\ (£/kW)\ x\ Power$

Typical cost of power electronics circuitry of dc-dc power converters would be around £17/kW.

Cost of retrofit, or installation cost on new trains, C_γ, C_i

The cost of retrofit, C_γ, is used if existing trains are converted, or the installation and testing cost of new trains, C_i , alternatively can be assumed. This cost is assumed to be proportional to the total cost of the storage device defined by, $\mathit{Storage\ Cost} = C_s + C_p + C_c$. A 10% allowance of the total cost of the storage device may be allowed for this.

Cost of gap automatic detection system on the train C_g

The cost of gap automatic detection equipment, C_g , is fixed per train and assumed to be £20k.

The total cost per train can, therefore, be summarised in the following equation:

$$\boxed{Cost_{per\ train} = 1.1\left(1.3\, CellCost(\text{£}/kWh) \times Energy + ConverterCost(\text{£}/kW) \times Power\right) + C_g}$$

Where $CellCost\ (\text{£}/kWh)$ is £16/Wh (or £16,000/kWh), $ConverterCost\ (\text{£}/kW)$ is £17/kW, $Energy$ and $Power$ are the energy and power requirements of the storage device and C_g is £20k, cost of gap automatic detection equipment.

For example, a 1MW, 4kWh super capacitor storage cost, applying the above equation, would be around £130k.

5.1.3 Cost of Enabling Work

Under the enabling work the cost components considered are:

C_d Development cost

C_a Approvals and acceptance cost

C_n Contingencies

Development, approval and acceptance and contingency costs C_d, C_a , C_n

The development cost C_d and approval and acceptance cost C_a are fixed, and required once only, at the beginning of the project. These costs are very high for prototype equipment, but once proven they are reduced, or diminish, when the system is produced on large scale.

The development cost comprises the cost of developing, testing and certifying a new system plus a margin for the manufacturer. The approval and acceptance costs are in the form of implementations, developing standards, setting regulations, etc.

The development cost, C_d, and approval and acceptance cost, C_d, plus adding additional cost for contingencies, C_n , are treated as fixed cost, $EnablingWorkCosts$. It is difficult to estimate this cost, but an approximate figure of a few million pounds (say 5 million) can be assumed for this purpose.

5.1.4 Total Initial Fixed Cost

For N trains the total cost of storage devices, therefore, can be expressed by the following equation, (alternatively, the fixed cost may be subtracted from the initial cost reduction in electrification to simplify the calculations).

$$\boxed{Total\ Cost\ Of\ Storage\ Devices = N \times Cost_{per\ train} + EnablingWorkCosts}$$

For example, 100 trains equipped with 1MW, 4kWh super capacitor storage devices the total cost of storage devices would be around £14M. Clearly, this figure is calculated as an initial cost. If, for example, the storage devices are rolled out over a number of years then the cost must be corrected to Net Present Value (NPV) along with others variable costs, as shown in the following section. It should be noted that with different rolling stock types using different storage sizes the above formula may be modified to the following, with i as the type of train:

$$\boxed{Total\ Cost\ Of\ Storage\ Devices = \sum_i N_i \times Cost_{per\ train\ i} + EnablingWorkCosts}$$

5.2 Variable Costs

5.2.1 Maintenance

Unlike batteries or flywheels, super capacitor based storage systems have a lifetime of more than one million duty cycles with very limited maintenance required. However, the whole system will have to be checked regularly to ensure a proper voltage balancing and the isolation of the circuits. For this purpose the annual maintenance cost is assumed to be 2% of the super capacitor storage device cost, $StorageCost$.

$C_{maintenance} = 0.02 \times StorageCost$

With discontinuous electrification it is expected that less OHL maintenance would be required, particularly in complex areas where gaps are introduced. However, there will also be additional maintenance requirement for the automatic gap detection equipments. For simplicity, and for the purpose of this study, the overall cost of infrastructures maintenance is assumed to be the same as for normal electrification, ie the cost of detection system maintenance is offset by the OHL maintenance reduction.

5.2.2 Equipment replacement

Super capacitors have long lifetime compared with batteries. They should last between 10 and 20 years when used in heavy transport applications. The end of life of a super capacitor is not reported to be a dramatic failure but a loss of performance. It is characterized as 30% drop in capacitance from nominal, or increase of 100% in ESR.

As a result, replacement will occur at least once in lifetime of the train and will generate replacement costs: purchase of new components (mainly super capacitors cells), immobilization of the vehicle during replacement and dismantling and mounting of the new system. For the purpose of analysis it is assumed that super capacitor storage devices are replaced every 15 years and at the same cost of the original devices corrected to NPV. Clearly, the last assumption ignores a possible future cost reduction of super capacitors. This may be justified by the uncertainties of future trends.

5.2.3 Additional cost functions

There are variable running costs incurred in running a discontinuous electrification scheme, these are listed below. A simplified cost function is allocated for each item and discussed briefly. It is recognised that a more detailed analysis will be required for each item addressed.

Increased energy cost

With storage devices, trains will consume slightly more energy. This is because, the energy required to move a train through a gap would have to be stored in the storage device and released again. As such the round efficiency of the storage device must be considered. For super capacitors it is in the order of 90%. It should be noted that this topic is directly linked to the train performance, eg more coasting through gaps means energy reduction at the expense of journey times. This subject is outside the scope of this study.

For 32 gaps in our example, if we assume the average energy required per gap is 1kWh, and the train service is half hourly, for 10 hours a day, and for 365 days a year, the annual increase in energy would be around 50MWh. The energy cost is assumed to be increasing with time steadily, and starting in the first year at a figure of £150/MWh.

CO_2 emission cost

There are several studies carried out in this area, where a range of figures for carbon cost have been reported. A reasonable cost of CO_2 emission reported to be around £20 per tonne, with the electricity production mix carbon emissions varies between 0.4 to 0.6 kg/kWh.

However, at this stage the environmental impacts may be ignored and not considered in the calculations.

Passenger seats lost to the storage device

A passenger seat costs an annual cost that can be calculated to a reasonable accuracy. However, for simplicity the storage devices are assumed to be fitted under the frame and there will be no loss of passenger seats.

It should be noted that this assumption may not hold true as, for safety reasons, the storage devices may not be allowed to be fitted underneath the train.

Note that commercially available super capacitor storage devices, mainly built for trams, are usually fitted on the roof (see Appendix section 13). However, fitting these equipments on the roof will defy the purpose in our application, whereby gaps are considered because of small OHL clearances.

Insurance premium

Insurance premiums are usually linked to risk. The storage devices, for the purpose of this study, are assumed safe and therefore would not result in increased insurance.

Safety

The storage devices are assumed safe in our study, and as such there will be no additional costs.

Reliability

Reliability is difficult to assess at this stage. It is expected, however, that the OHL reliability will be improved as complex areas are eliminated. However, the trains' reliability is expected to be worse since additional equipments are added. It is assumed that no additional costs are incurred in this assessment.

Operating Risks and Trains Compatibility

There are complex issues surrounding trains compatibility in such applications. This subject needs detailed analysis and is outside the scope of this report. For the purpose of the analysis presented here, it is assumed that there are no cost implications due to train compatibility.

Sustainability and recyclability

Little is known about sustainability and recyclability of super capacitors as these devices are not produced at a full industrial scale. This issue is outside the scope of this study and will not be considered in the analysis.

5.3 Cost-Benefit Analysis

The objective of this exercise is to estimate the economic impacts of discontinuous electrification in the case study example given below. It must be pointed out that such analysis requires a multidisciplinary approach involving all partners concerned and investigation must focus on line specific details. The exercise presented in this section, therefore, must be used for indicative purposes only.

The cost-benefit analysis (CBA) technique is used to evaluate the economic feasibility of discontinuous electrification schemes employing onboard super capacitors. For this purpose it is necessary to identify all the costs and benefits related to this application. The CBA is also very useful tool for comparison of investment options in different energy storage systems.

In view of many uncertainties, the decision process is based on summing up all variable costs occurring during the lifetime and compares it with the reduction in electrification investment cost, cost of storage devices and development cost. The scheme can then be considered as profitable when the cost reduction in the electrification scheme exceeds the lifetime system costs.

The approach consists of calculating the Net Present Value (NPV), which is defined as the total present value of a series of future cash flows. In order to discount these cash flows to their present values, a rate of discount must be specified. One of the major difficulties when assessing public funded projects is the determination of the discount rate. Indeed, the discount rate has a straight influence on the results of the NPV. A higher rate means a preference for the present time whereas a lower rate shows that more attention is given to future generations. In this study, a discount rate of 3% has been assumed. This figure is, generally, considered acceptable in railway projects.

If we assume the initial fixed cost of development and approval costs, $FixedCosts$, say, £3M, this figure can be subtracted from the reduction in electrification cost of £60M (see section 5.1.1). The net saving is £57M.

The numbers and type of trains operating on the line are assumed in Table 10. The power and energy capacities are assumed to be of standard size requirements for the type of train. The trains are assumed to be rolled out over five years, and the storage devices useful life is fifteen years. Replacement of the storage devices after five years is assumed to be rolled out in five years.

Power kW	Energy kWh	Train Type	Numbers
1000	4	Suburban	60
2000	8	Regional	40
3000	10	Intercity	20

Table 10 - Number and types of trains required to be fitted with energy devices the power and energy specified

The NPV of variable costs, including energy storage devices, over 30 years service, are shown in Table 11. The cost of energy is assumed to increase by 10% annually. The NPV is calculated using the following formula,

$$NPV = \sum_{n=1}^{N} \frac{VariableCost_n}{(1+r)^n}$$

Where r is the rate of discount assumed to be 3%, N is number of years of service assumed 30. The net cost is £41M based on NPV. This compares with £60M initial saving in electrification assumed. This suggests, given the assumptions made, that the scheme is viable.

Year	Running Costs			
	Storage	Maintenance	Energy	NPV
1	£4,273,760	£0	£7,500	£4,281,260
2	£4,273,760	£85,475	£8,250	£4,240,277
3	£4,273,760	£170,950	£9,075	£4,198,120
4	£4,273,760	£256,426	£9,983	£4,154,897
5	£4,273,760	£341,901	£10,981	£4,110,711
6	£0	£427,376	£12,079	£379,078
7	£0	£427,376	£13,287	£369,048
8	£0	£427,376	£14,615	£359,379
9	£0	£427,376	£16,077	£350,066
10	£0	£427,376	£17,685	£341,102
11	£0	£427,376	£19,453	£332,483
12	£0	£427,376	£21,398	£324,204
13	£0	£427,376	£23,538	£316,262
14	£0	£427,376	£25,892	£308,653
15	£0	£427,376	£28,481	£301,375
16	£4,273,760	£427,376	£31,329	£3,037,589
17	£4,273,760	£427,376	£34,462	£2,951,068
18	£4,273,760	£427,376	£37,909	£2,867,200
19	£4,273,760	£427,376	£41,699	£2,785,916
20	£4,273,760	£427,376	£45,869	£2,707,151
21	£0	£427,376	£50,456	£264,564
22	£0	£427,376	£55,502	£259,571
23	£0	£427,376	£61,052	£254,907
24	£0	£427,376	£67,157	£250,576
25	£0	£427,376	£73,873	£246,581
26	£0	£427,376	£81,260	£242,928
27	£0	£427,376	£89,386	£239,620
28	£0	£427,376	£98,325	£236,665
29	£0	£427,376	£108,157	£234,069
30	£0	£427,376	£118,973	£231,841
			Total	**£41,177,162**

Table 11 - NPV of variable costs incurred over the lifetime of the system

5.4 Costs for Minimum Storage

The CBA case study example presented in sections 5.1, 5.2 and 5.3 is based on specific assumptions where the storage devices are assumed to have standard sizes for the train types specified. However, these sizes can be minimised further by designing the storage device to meet the minimum requirements, rather than designing for a standard size.

The two hybridisation options suggested in section 4.7, for frequent cycling using super capacitors and emergency storage using small batteries, are considered in this assessment. The criterion for both options is to design a storage device capable of delivering sufficient energy to move the train outside a gap starting from standstill. The initial cost and NPV lifetime cost of the storage devices are determined per storage system per train type. These costs can be used in the CBA in the same way as was shown earlier.

For the frequent cycling case the costs per storage device per train are shown in Table 12 (see section 4.7.1, Table 4 and Table 5).

	Gradient	Gap length (m)	Storage Mass (tonne)	Initial Cost £k / train	NPV Cost £k / train	Minimum Energy (kWh)	Power Capacity (kW)
4-car Class 365	flat	100	0.4	£31,053	£95,026	1.09	220
	flat	300	0.6	£44,924	£121,312	1.59	350
	flat	500	1	£63,138	£155,827	2.1	700
	1%	100	0.7	£51,350	£133,490	1.83	400
	1%	300	1.35	£100,120	£225,909	3.7	720
	1%	500	2.05	£151,384	£323,056	5.63	1100
9-car Class 390	flat	100	1.15	£85,769	£198,714	3.13	650
	flat	300	1.4	£103,904	£233,080	3.8	800
	flat	500	1.7	£126,366	£275,645	4.7	900
	1%	100	1.9	£145,625	£312,141	5.46	1000
	1%	300	3.9	£278,804	£564,517	10.3	2200
	1%	500	5.4	£403,130	£800,118	15.08	3000

Table 12 - Costs of minimum size of super capacitors for a start-from-standstill operation. The maximum exit speed is 16 kph.

For the case of emergency storage scheme small batteries are recommended (see section 4.7.2, Table 6 and Table 7). The initial costs and NPV lifetime costs of these batteries are expected to be even smaller, particularly with the new generation of high specific power lithium ion batteries.

There is no readily available data for the new generation of batteries. However, the current cost of lithium ion batteries is approaching $500/kWh. If we use this figure for the new high specific power batteries it would bring costs below that of Table 12 for super capacitors.

6 Discrete Electrification

The term discrete electrification refers to OHL gap lengths in the order of a few kilometres. These lengths are compared with hundreds of metres for discontinuous electrification. The key design criterion in discrete electrification is to build a sufficiently large onboard storage device capable of powering the train through substantial distances. Evidently, with the available technologies, the only device that fulfils this task is battery.

The advent of high efficiency, long life, fast charging / discharging and high specific energy new batteries would make this application more feasible. The specific energy density of a lithium ion battery, for example, is three to four times larger than lead acid battery. As such, for the same weight a lithium ion powered Electric Vehicle (EV) would have three to four times the range of lead acid.

The key design aspects in discrete electrification is to optimise the operating time, charging time, DOD level and the consequent useful life, weight and volume of the battery. All these parameters can be optimised by the choice of the battery type and size.

There are two main issues to be considered when batteries are used in this application, cost and useful life. Whilst new batteries promise better performance and longer life their cost is considerably higher. Furthermore, the markets of new batteries are not well established in terms of supply, sustainability, recycling, etc. In addition, the new generation of batteries require more complicated management systems which further add to cost and complexity.

Compared with hybrid electric applications, a battery in discrete electrifications would have much shorter useful life because of the high levels and frequencies of the DOD. Furthermore, whilst coasting can be used in discontinuous electrification it is not possible with discrete electrification. The entire fleet must be equipped with storage devices. There is no scope for operating existing trains without storage devices, and clearly, this will put severe constraints on train compatibility and operation.

In conclusion, the large cost and limited life of existing batteries, and the operating constraints, make discrete electrification unviable using current technologies. However, future battery technologies may promise breakthroughs which could make discrete electrification feasible.

6.1 Case for Severn Tunnel and Class 390

The Severn Tunnel is more than 7 km in length and runs beneath the Bristol Channel on the Great Western line. In considering electrification of the Great Western Main Line, the Severn Tunnel requires a major upgrade at considerable cost to enable conventional electrification. For this reason the feasibility of discrete electrification is assessed on the bases that the tunnel is left unelectrified.

An approximate estimation of the battery required to run 'Intercity' train (equivalent to 7-car Class 390 Pendolino train) through the tunnel has been carried out using the ESSRA software (see section 7). The results are shown below.

A 6 tonne lithium ion battery occupying 3.9 cubic metre at an initial cost of approximately £300,000 to £500,000, estimated at current prices, would be required to achieve full performance. The maximum power capability of the battery is 2.8 MW at 20% DOD giving approximate useful life of five years. The train can achieve full performance in normal conditions, and also assuming a single emergency stop inside the tunnel.

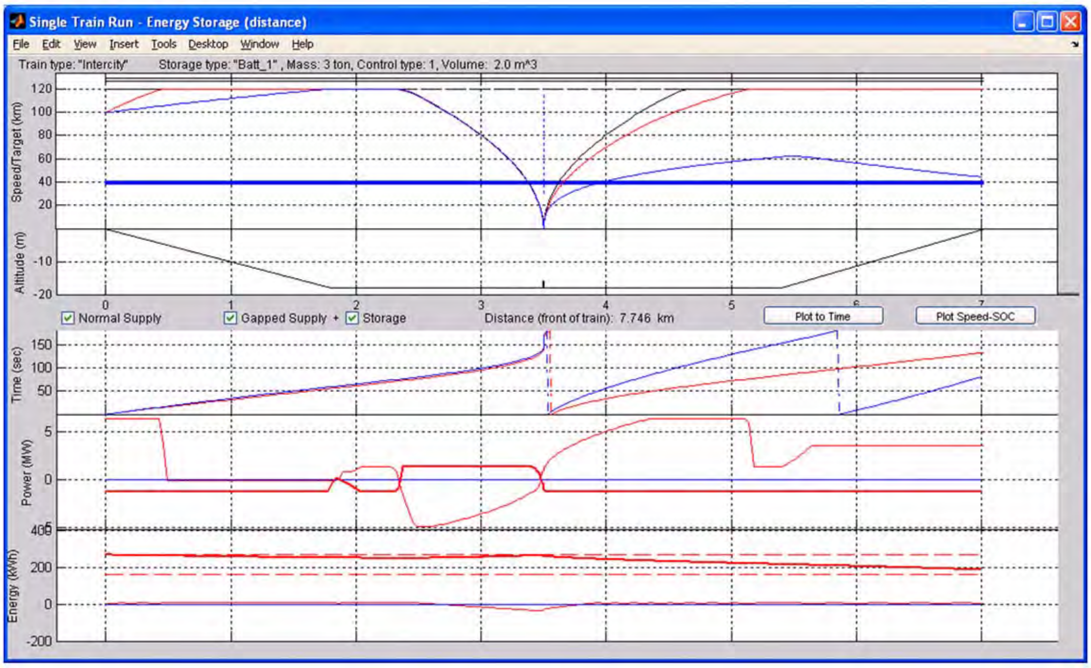
However, the storage device can be halved in size by doubling the DOD. A 3 tonne, 1.4 MW, 2.0 cubic metre battery can support the service with a single stopping point, but at reduced performance. The useful life of the battery would be reduced to possibly 3 years or less (see output results from ESSRA in Figure 14).

If the 3 ton lithium-ion battery is replaced with, for example, a lead acid battery the weight and volume would be three to four times larger and the useful life would be much shorter. However, the cost of lead-acid battery is at least one tenth of that of lithium ion. The weight of a lead acid battery would be in the order of ten to twelve tonnes, and would need replacing every, possibly, six months at cost of less than one tenth of a lithium ion battery.

It should be noted that in such a scheme every train running through the tunnel must be equipped with an appropriate storage device as coasting is not possible.

Given the factors described above, it looks very difficult to justify the scheme, whether using state of the art lithium ion batteries, or conventional lead acid batteries.

However, future technologies may hold the key to make this application viable. But this is very difficult to predict at this stage.



Train type: "Intercity"   Storage type: "Batt_1" , Mass: 3 ton, Control type: 1, Volume: 2.0 m^3

☑ Normal Supply ☑ Gapped Supply + ☑ Storage   Distance (front of train): 7.746 km

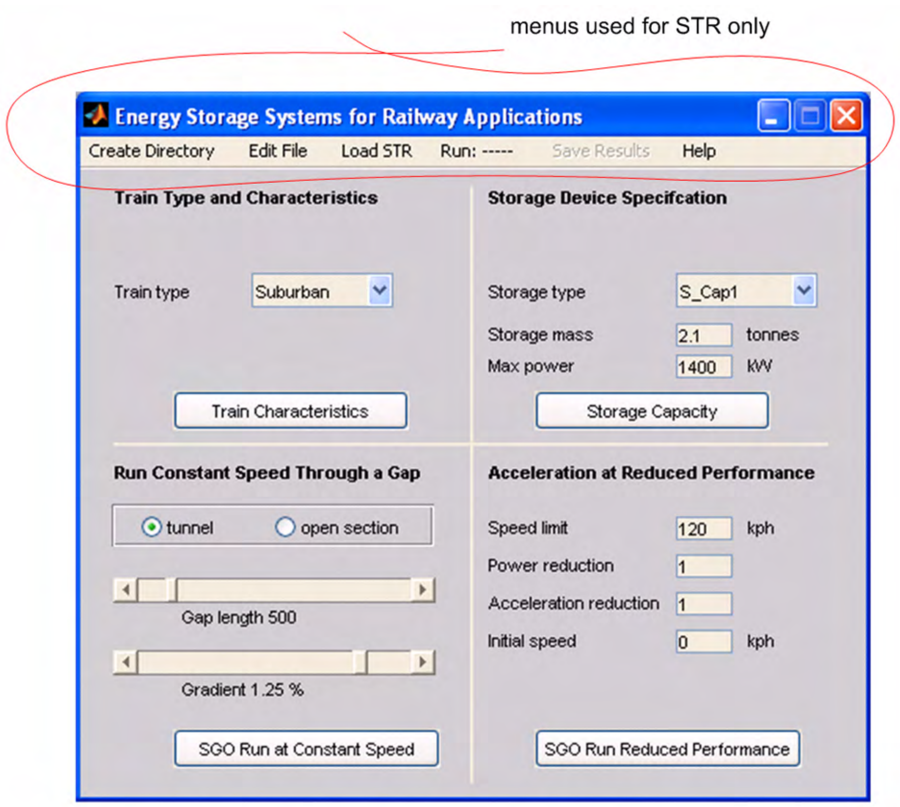
Figure 14 - Severn Tunnel ESSRA example, Class 390 equipped with 3 ton lithium ion battery

7 Train Energy Storage Simulator ESSRA

A high-level software tool has been developed to asses the performance of onboard storage devices at the introduction of coasting, discontinuous or discrete electrification schemes. This software is designed to be used for high level design to assess and evaluate these schemes. It is not intended to be a detailed design tool and as such further work will be required should a system design exercise is undertaken.

Detail of the modelling methodology is given in section 12, and a 'User and Installation Manual' is provided in Reference 2. This model has been developed in Matlab and cross compiled into Windows environment enabling running on a desktop. The model is available on CD and can be obtained from RSSB.

The base window of ESSRA is shown in Figure 15. The software can be used for two purposes; running a Single Gap Operation (SGO), or running a Single Train Run (STR).



menus used for STR only

Energy Storage Systems for Railway Applications
Create Directory
Edit File
Load STR
Run: -----
Save Results
Help
Train Type and Characteristics
Storage Device Specifcation
Train Characteristics
Storage Capacity
Run Constant Speed Through a Gap
Acceleration at Reduced Performance
SGO Run at Constant Speed
SGO Run Reduced Performance

Train type: Suburban

Storage type: S_Cap1

Storage mass: 2.1 tonnes

Max power: 1400 kW

● tunnel ○ open section

Gap length 500

Gradient 1.25 %

Speed limit: 120 kph

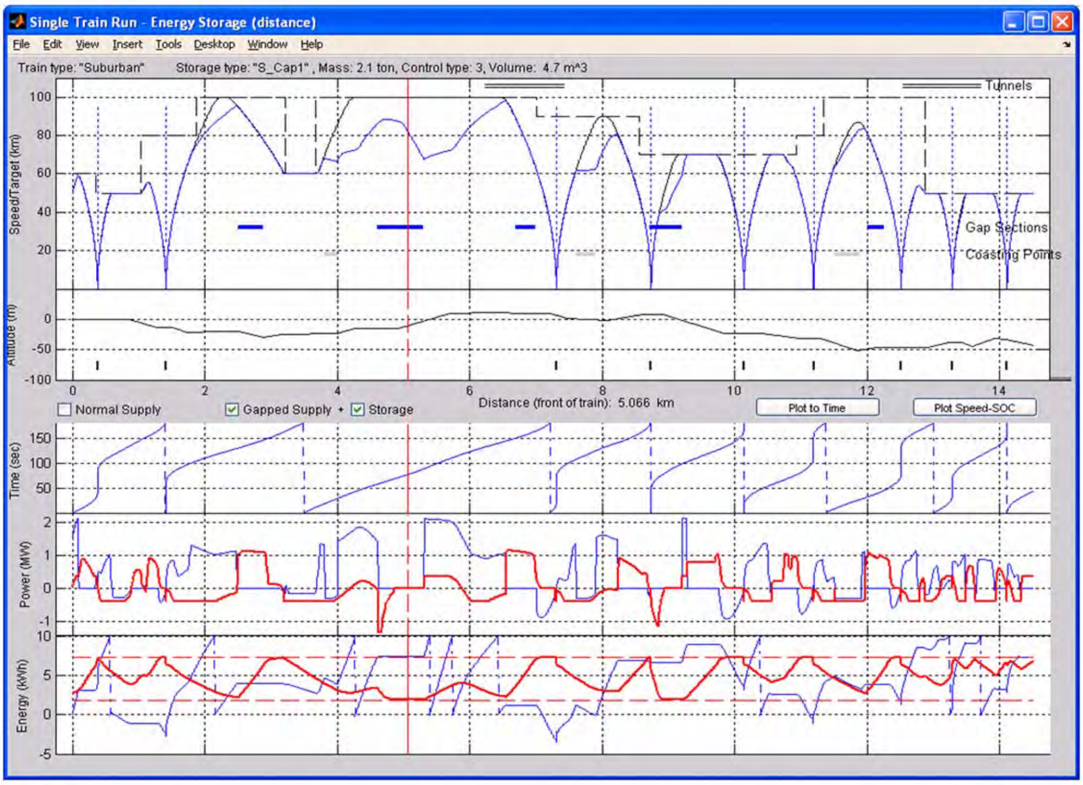
Power reduction: 1

Acceleration reduction: 1

Initial speed: 0 kph

Figure 15 - Base window for ESSRA

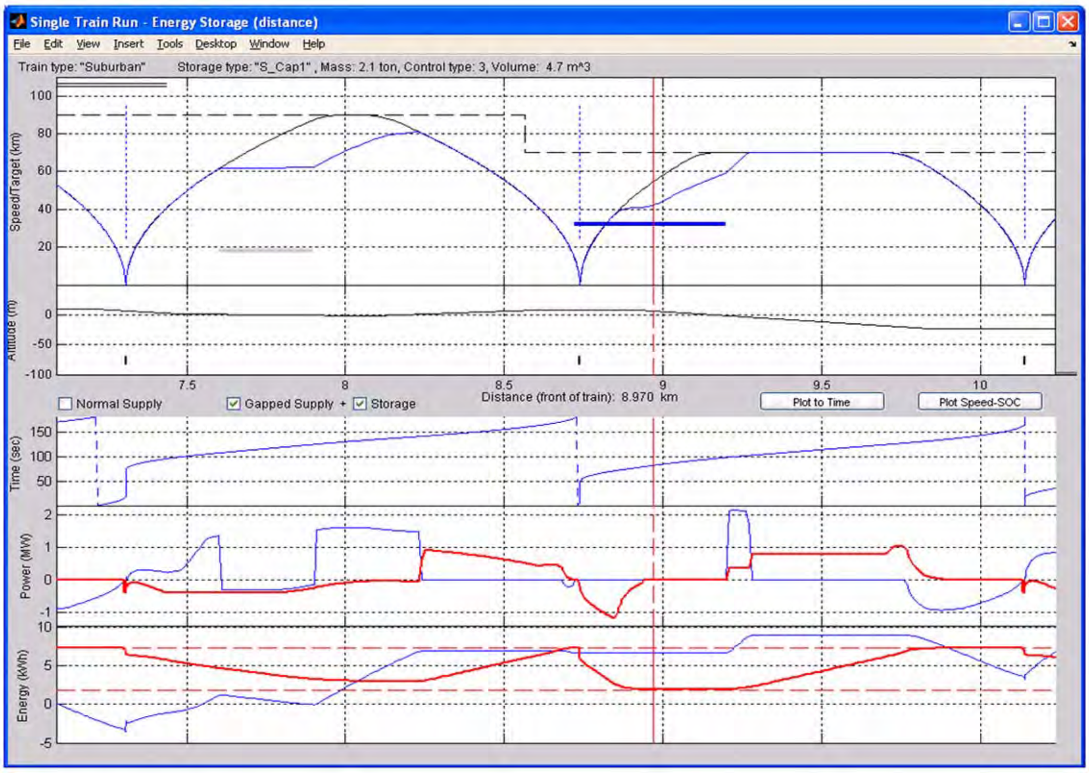
The analysis of SGO can be performed using the base window's buttons, sliders, text, etc. The user does not need to use the menus (at the top of Figure 15), at all, to run the SGO. The menus are used exclusively for the Single Train Run (STR). Typical output results of ESSRA are shown in Figure 16 and Figure 17. For further details refer to Reference 2.



Train type: "Suburban"   Storage type: "S_Cap1" , Mass: 2.1 ton, Control type: 3, Volume: 4.7 m^3

Distance (front of train): 5.066 km

Figure 16 - Typical distance plots



Train type: "Suburban"   Storage type: "S_Cap1" , Mass: 2.1 ton, Control type: 3, Volume: 4.7 m^3

☐ Normal Supply ☑ Gapped Supply + ☑ Storage

Distance (front of train): 8.970 km

Figure 17 - Left-click at a specified distance and zoom in or out using the mouse roller

8 Conclusions

Discontinuous electrification, in conjunction with coasting, is feasible. Standard trains can be operated on such schemes, relying on coasting but will require a special operating regime. Trains may be fitted with either super capacitors for frequent recycling pattern of operation, or small emergency batteries used only when required. Frequent cycling may be used for cases where gaps are required at, or near stations, and also can be used for capturing braking energy. Emergency battery storage may be used should trains stop within a gap during unscheduled events. The existing train auxiliary battery may be designed to serve both purposes of supplying the auxiliary load and emergency traction load for gapping.

An indicative assessment of the business case for discontinues electrification suggests that these schemes are viable using existing technologies. However, it is recommended that a study is undertaken to accurately estimate the cost of electrifying a specific route with normal OHL compared with discontinues. This is a key parameter in determining the feasibility of such a system.

Discrete electrification, given the available energy storage technologies, seems difficult to justify. Whether using state of the art lithium ion batteries or conventional lead acid batteries the scheme does not seem viable. One of the problems with this scheme is that the entire fleet of trains must be fitted with storage devices, which introduces severe constraint on operation. However, future technologies may hold a key to make this application viable. However, this is very difficult to predict at this stage.

9 References

1 RSSB R&D Project T779 stage-1 report, "Energy Storage Systems for Railway Applications - phase 1", issue 2, dated March 2009.

2 RSSB R&D Project T779, "Onboard Energy Storage Systems for Railways Applications, ESSRA Model, Installation and User Guide", issue 1, dated October 2009.

3 RSSB R&D Project T777, "Understanding the Effect of 'Gaps' in Electrical Continuity of the Traction Contact System".

4 RSSB R&D Project T778, "Feasibility Study into Raising and Lowering Pantographs whilst Trains are in Motion".

5 RSSB R&D Project T633, "Study on further Electrification of Britain's Railway Network".

10 Appendix: Train Characteristics

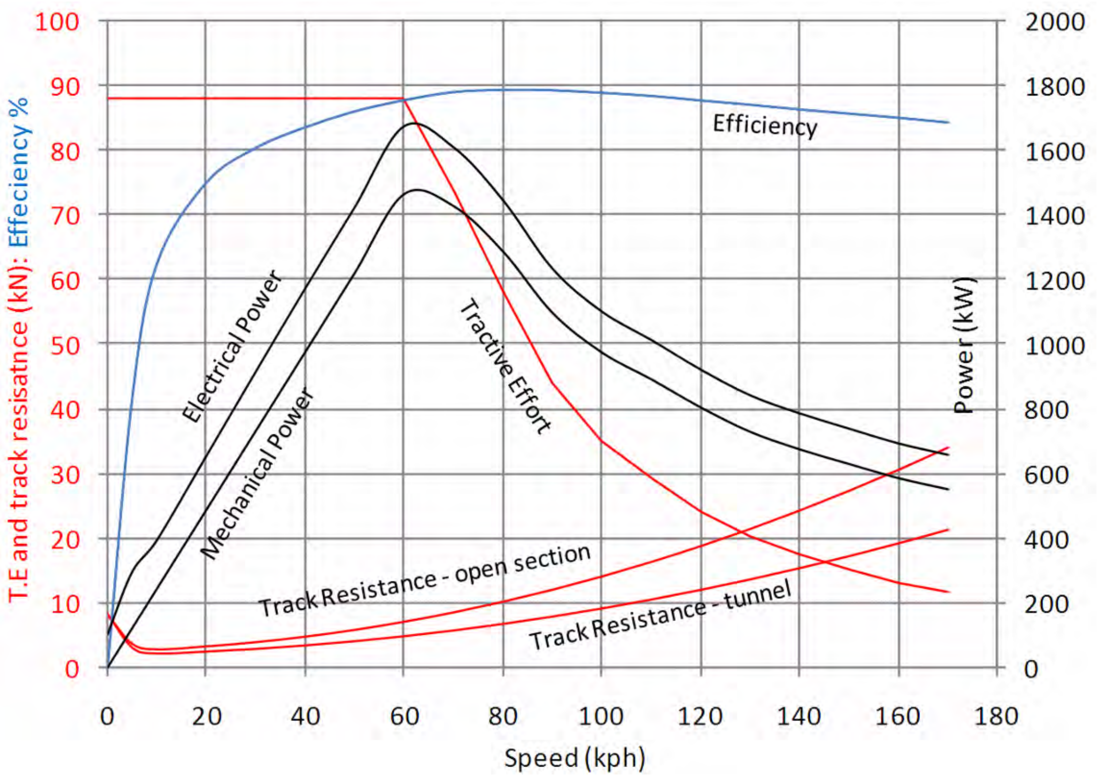


Figure 18 - Suburban train characteristics based on 4-car class 317, crush load mass 177 tonnes.

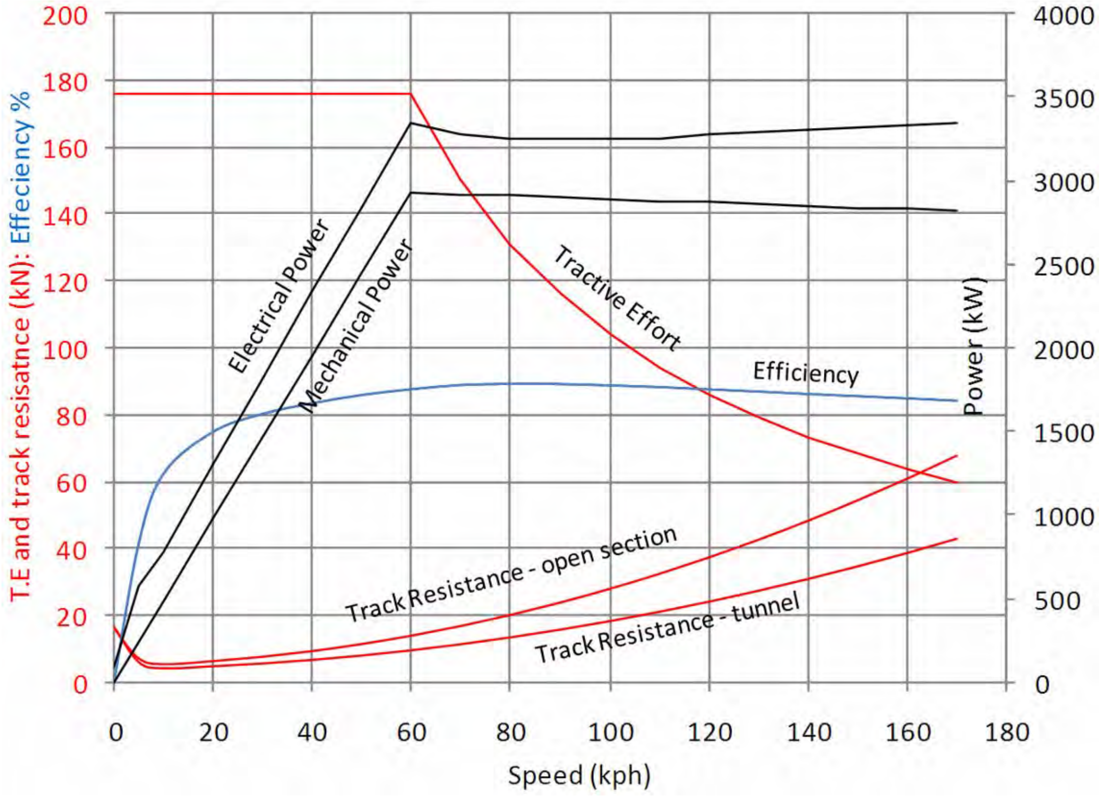


Figure 19 - Regional train characteristics based on 8-car class 317, crush load 256 tonnes

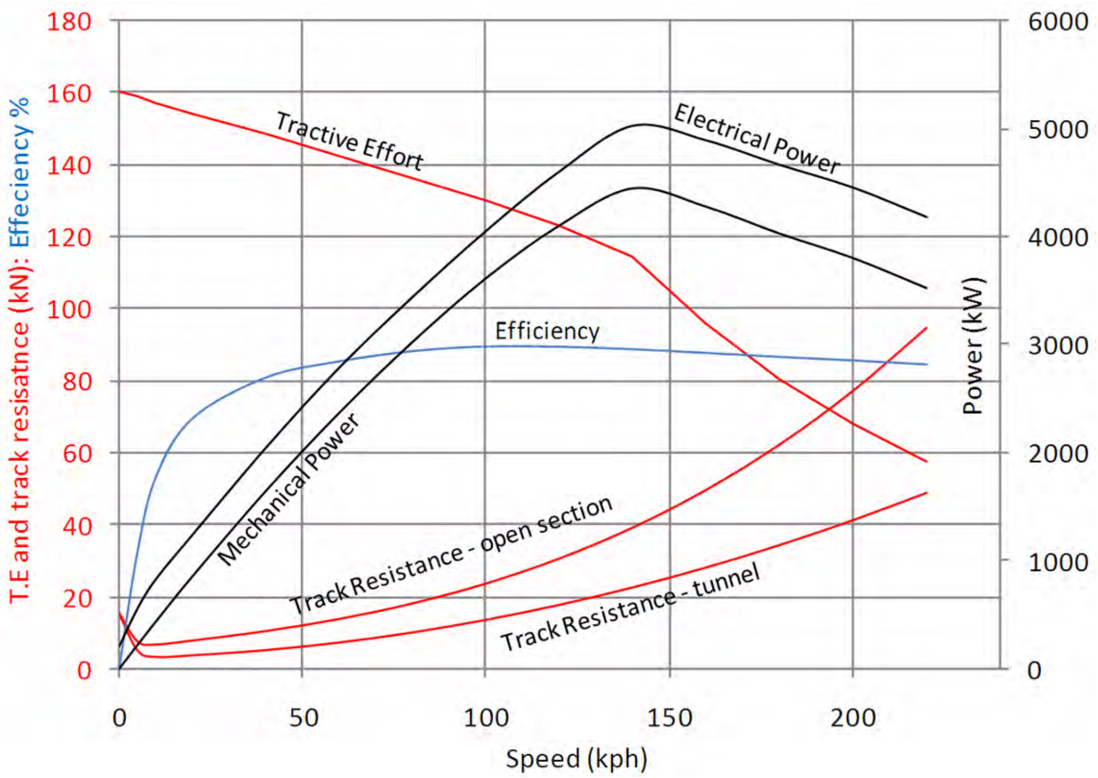


Figure 20 - Intercity train based on HST class 91, crush load 496 tonnes

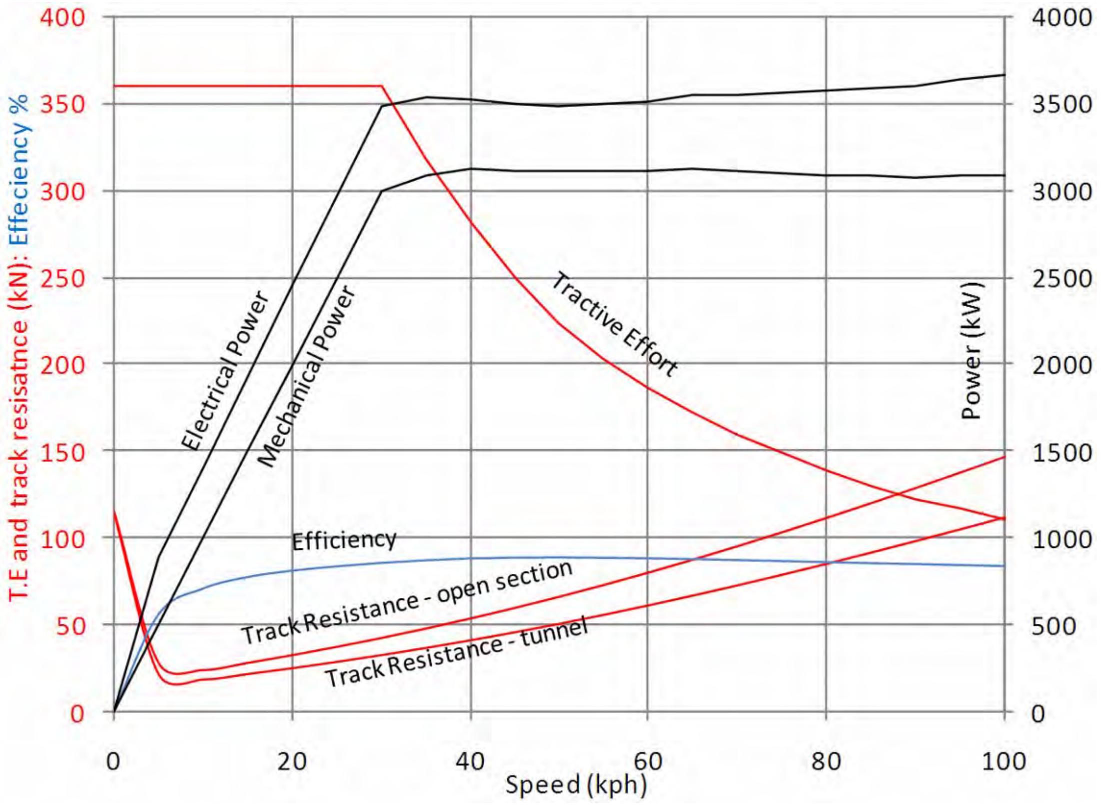


Figure 21 - Freight train based class 6, full load 1724 tonnes

11 Appendix: Indicative Storage Requirements

Suburban Train Storage Requirement																
Gap Length (m)	S_Cap1				S_Cap2				Batt_1				Batt_2			
	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)
100					0.52	75	0.887 1.058	7,434 8,870								
200	1.0	55	2.529 2.882	21,199 24,157												
300	1.2	75	3.035 3.459	25,439 28,988									0.85	6	0.397 0.453	71,400 81,600
400	1.6	75	4.047 4.612	33,918 38,651									0.9	8	0.420 0.480	75,600 86,400
500	1.9	75	4.806 5.476	40,278 45,898									0.9	10	0.420 0.480	75,600 86,400
1000													1	18	0.467 0.533	84,000 96,000
2000									1.7	15	1.333 1.473	204k 265k	1	37	0.467 0.533	84,000 96,000
3000									1.7	22	1.333 1.473	204k 265k	1	56	0.467 0.533	84,000 96,000
4000									1.7	29	1.333 1.473	204k 265k	1	72	0.467 0.533	84,000 96,000
5000									1.7	35	1.333 1.473	204k 265k	1.15	80	0.537 0.613	96,600 110k

Regional Train Storage Requirement																
Gap Length (m)	S_Cap1				S_Cap2				Batt_1				Batt_2			
	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)
100					1.3	75%	2.218 2.646	17,156 20,469								
200	2.4	50	6.071 6.918	50,878 57,977												
300	2.8	70	7.082 8.071	59,357 67,640									2.2	5.2	1.027 1.173	184k 211k
400	3.5	75	8.853 10.088	74,197 84,550									2.3	7	1.073 1.227	193k 220k
500	4.4	75	11.129 12.682	93,276 106k									2.5	8	1.167 1.333	210k 240k
1000													2.2	17	1.027 1.173	184k 211k
2000									3.8	14	1.773 2.027	319k 364k	2.2	35	1.027 1.173	184k 211k
3000									3.8	21	1.773 2.027	319k 364k	2.2	52	1.027 1.173	184k 211k
4000									3.8	28	1.773 2.027	319k 364k	2.2	70	1.027 1.173	184k 211k
5000									3.8	35	1.773 2.027	319k 364k	2.5	80	1.167 1.333	210k 240k

Intercity Train Storage Requirement																
Gap Length (m)	S_Cap1				S_Cap2				Batt_1				Batt_2			
	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)
100					1.6	75%	2.729 3.256	22,875 27,292								
200	3.7	42	9.359 10.665	78,436 89,381												
300	4.3	57	10.876 12.394	91,156 103k												
400	4.5	75	11.382 12.971	95,396 108k									3.3	6	1.554 1.776	279k 319k
500	5.5	75	14.165 16.141	118k 135k									3.5	7	1.633 1.867	294k 336k
1000													3.2	15	1.493 1.707	268k 307k
2000									5.8	12	3.867 5.027	696k 904k	3.2	30	1.493 1.707	268k 307k
3000									5.8	18	3.867 5.027	696k 904k	3.2	45	1.493 1.707	268k 307k
4000									5.8	23	3.867 5.027	696k 904k	3.2	60	1.493 1.707	268k 307k
5000									5.8	29	3.867 5.027	696k 904k	3.2	76	1.493 1.707	268k 307k

Freight Train Storage Requirement																
Gap Length (m)	S_Cap1				S_Cap2				Batt_1				Batt_2			
	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)	Mass (ton)	DOD %	Volume (m^3)	Cost ($)
100	3.1	75	7.841 8.935	65,717 74,887									2.5	5.4	1.667 1.167	210k 240k
200	6.0	75	15,176 17,294	127k 145k									2.8	10	1.307 1.493	235k 268k
300													3.2	13	1.493 1.707	268k 307k
400													3.3	17	1.540 1.760	277k 316k
500													3.4	20	1.587 1.813	285k 326k
1000									5.0	20	3.333 4.333	420k 480k	3.2	44	1.493 1.707	268k 307k
2000									5.5	35	3.667 4.767	660k 858k				
3000									5.5	52	3.667 4.767	660k 858k				
4000									5.5	70	3.667 4.767	660k 858k				
5000									5.8	80	3.867 5.027	696k 904k				

12 Appendix: Modelling Methodology

As part of the T779 *Energy storage systems for railway applications*, project, a high-level software tool has been developed to assess the performance of onboard storage devices following the introduction of 'coasting', 'discontinuous' and 'discrete' sections within electrification schemes. This software tool can be used for the definition of high level design to meet the requirements of these schemes. It is not intended to be a detailed design tool and as such further work will be required for the tool to provide a full scale system design.

This Appendix provides description of the modelling methodology and approach. The software tool is called *Energy Storage Systems for Railway Applications*. The software must be used in conjunction with the project documentation as described in the reference list.

The data provided for the train types are approximate for typical trains. A more accurate data would be required for better accuracy. For the storage devices the data included are for typical commercially available energy storage devices, bearing in mind some of the data is purely theoretical. Further detail can be found in the referenced reports.

12.1 Modelling Overview

An onboard storage device can be integrated with the traction equipment of a train in a series type hybridisation, as shown in Figure 22. The dc link is used to interface the traction inverter, auxiliary load, input converter and the additional storage device. The storage device is connected through a bi-directional dc-dc converter. The energy management system must ensure that the power summation at any moment in time must equal zero (see Figure 23).

With the exception of the auxiliary load, power can flow bidirectionally for traction, supply and the storage device. During regenerative braking power is fed to the dc link. This power is shared between the auxiliary and charging the storage device (if required), with the excess power fed back into the overhead line. Charging and discharging of the storage device is governed by the energy management system which balances all factors involved in the operation.

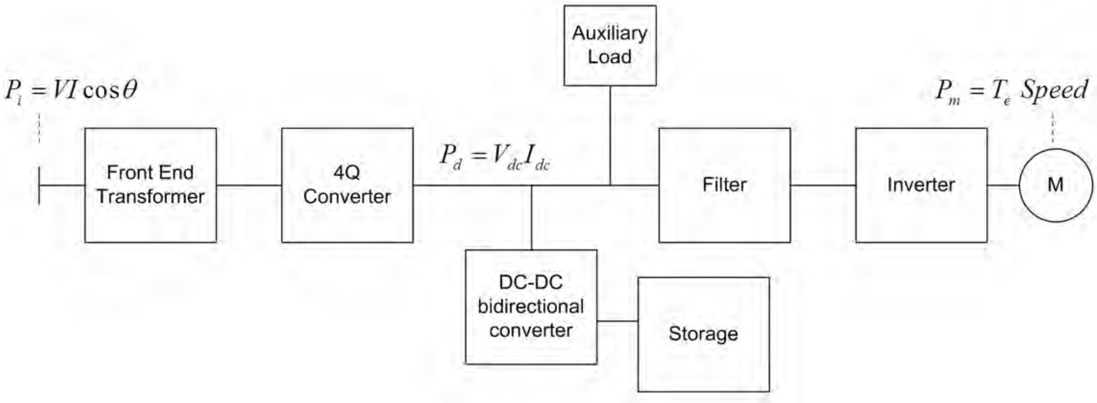


Figure 22 - Series type hybridisation of electric rail vehicle showing the power flow

Power losses occur with every transfer, from one device to another in all directions. The traction losses are in the inverter filter, inverter switching and through conversion from electrical to mechanical power in the traction motors. Losses in the supply (from the overhead line) occur in the line transformer and the 4-Q converter. All these losses occur in both directions of power flow.

For the storage device the losses occur during both charging and discharging resulting in a combined round efficiency. There are also losses due to leakages within the storage device, but these are small when compared with the charging and discharging losses.

The simulation is based on time sampling, whereby a specified sampling rate is used. The power summation at every sample is balanced to zero. For every sample, quantities such as voltage, current and power are determined for all the devices involved. The results are obtained for every sample and stored for the entire run, which can be post processed later.

Modelling of the auxiliary load and power supply is relatively easy. The auxiliary load can be assumed to be constant at all times. For the power supply, an equal efficiency in both directions can be assumed for both motoring and regenerative braking. These losses are mainly in the form of no load and copper losses in the transformer, and a nearly load independent losses in the 4-quadrant converter.

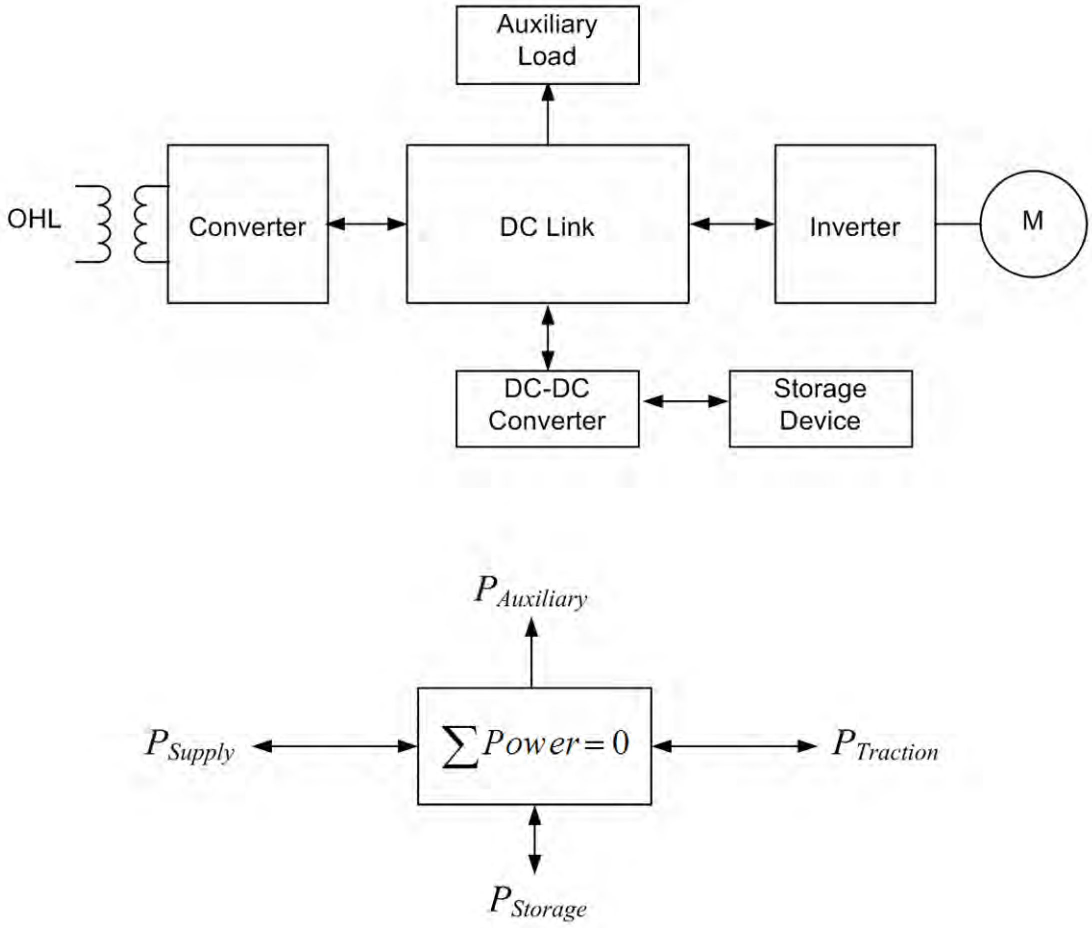


Figure 23 - Power balance at the dc link

The focus then will be on modelling the traction load and storage device controller and its relationship with the infrastructures. This is described in sections 12.2 and 12.3 respectively and the infrastructure is shown in section 12.5.

12.2 Train Model

To determine the power and energy requirements for a train operating on a defined track the standard equations of motion are applied. To apply these equations, the forces acting against the train during movement must be considered. These are:

- Train resistance force governed by Davis coefficients.
- Gradient force.
- Acceleration force.
- Curvature force and wind force.

The last two forces can be ignored in the analysis. The curvature force can be lumped with the train resistance and the wind forces are ignored for this high level assessment. The remaining forces, namely track, gradient and acceleration can be expressed in the following three equations respectively,

Train resistance $F_\gamma = A+B\,v+c\,v^2$

Gradient force $F_g = g\,M\,\sin(\alpha)$

Acceleration force $F_a = a\,M$

Where $A(kN/ton)$, $B(kN/ton/(m/s))$, and $C(kN/(m/s)^2)$ are the Davis coefficients.

B may be split into two parts, $B_1(kN/ton/(m/s))$ for rolling resistance, and $B_2(kN/(m/s))$ for aerodynamic resistance. B_1 and B_2 are related by two relationships as follows, $B = B_1 + B_2$ and $B1 \approx 0.1B$

$v(m/s)$ speed, $g(m/s)^2$ gravity $9.81(m/s)^2$, $M(ton)$ mass, α gradient angle (the term $\sin(\alpha)$ can be replaced by the percentage of gradient as the angle tangent is nearly equals the sine for small angles), and $a(m/s)^2$ train acceleration.

The mechanical power at the wheel-track interface can be expressed as,

$P_m = (F_\gamma + F_g = F_a)v$

The efficiency between the dc link and output power can be defined by the ratio,

$P_m/V_{dc}I_{dc}$

And the overall efficiency between the contact-wire to wheel-track can be expressed as,

$P_m/VI\cos(\theta)$, where $\cos(\theta)$ is the power factor.

Under coasting the deceleration rate can be defined as,

$dec = (F_\gamma + F_g)/M$

The energy can be obtained by integrating the power over the duration of operation, expressed in a digitised format as,

$$Energy = \sum_{i=1}^{N} \left(\frac{P_i + P_{i+1}}{2} \right) \Delta t$$

By applying the basic motion equations, outlined above, it is possible to determine the train power, energy, speed, etc. Determining these parameters will enable quantifying the size and type of the energy storage system to fit the purpose required.

For modelling purposes, four types of trains are considered and these are defined:

- Suburban: the train characteristics are based on 4-car Class 317 or 365/465 with full passenger load. The train resistance is provided for open section and tunnel section.
- Regional: the train characteristics are based on 8-car Class 317 or 365/465 with full passenger load.
- Intercity: the train characteristic is based on 9-cars + Class 91 hauled train or 9-car Class 390 with full passenger load.
- Freight: the train is based on Class 6 characteristics hauling a full load of 1,724 tonnes.

The efficiency of traction equipments is defined between the dc link and the output mechanical power at the wheels. Furthermore, the train resistance from standstill have been included in the model. This force is not accounted for in the Davis coefficients (see section 12.2). The terms used for the train types throughout this document are 'Suburban', 'Regional', 'Intercity' and 'Freight'.

Typical train characteristic is shown in Figure 24 (repeated for completeness).

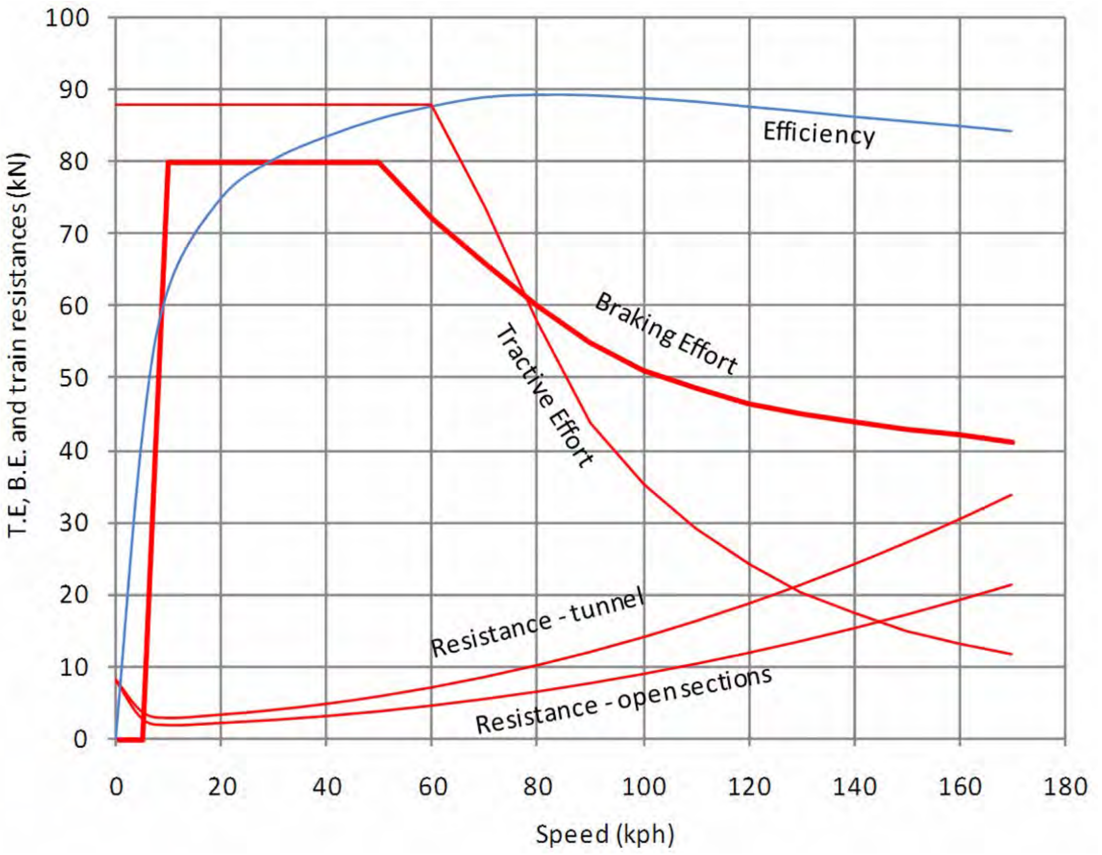


Figure 24 - Typical train characteristics

The efficiency shown is between the dc link and the delivered mechanical power. This enables determining the corresponding electrical demand at the dc link. Note in a standard train simulation it is slightly different, usually the tractive effort and traction current are expressed at different line voltages. Therefore the efficiency (if required) would be between the contact wire to the mechanical power delivered at the wheels.

12.3 Storage Systems Model

The storage device is charged and discharged through a bidirectional dc-dc converter. Losses occur in the storage device and the converter, and in both charging and discharging. The efficiency is usually determined for a round operation. These losses are relatively simple to calculate and depend on the type of storage device and converter.

Storage devices considered in the modelling are batteries, super capacitors, flywheels and future technologies such as nano technology. These have been given the following terms; 'Batt_1' for high energy battery (although lithium-ion is used in the examples, other batteries can be used by replacing the corresponding power and energy specifics), 'Batt_2' for high power battery, 'S_Cap1' and 'S_Cap2' for high energy and high power super capacitors respectively, 'Flywheel' for flywheels and 'Nano' for future technologies such as nano technology. Figure 25 (repeated for completeness) shows the energy and power specifics of these devices expressed on a Ragon plot. The generalised energy and power specifics in today's available storage devices are shown in Figure 26.

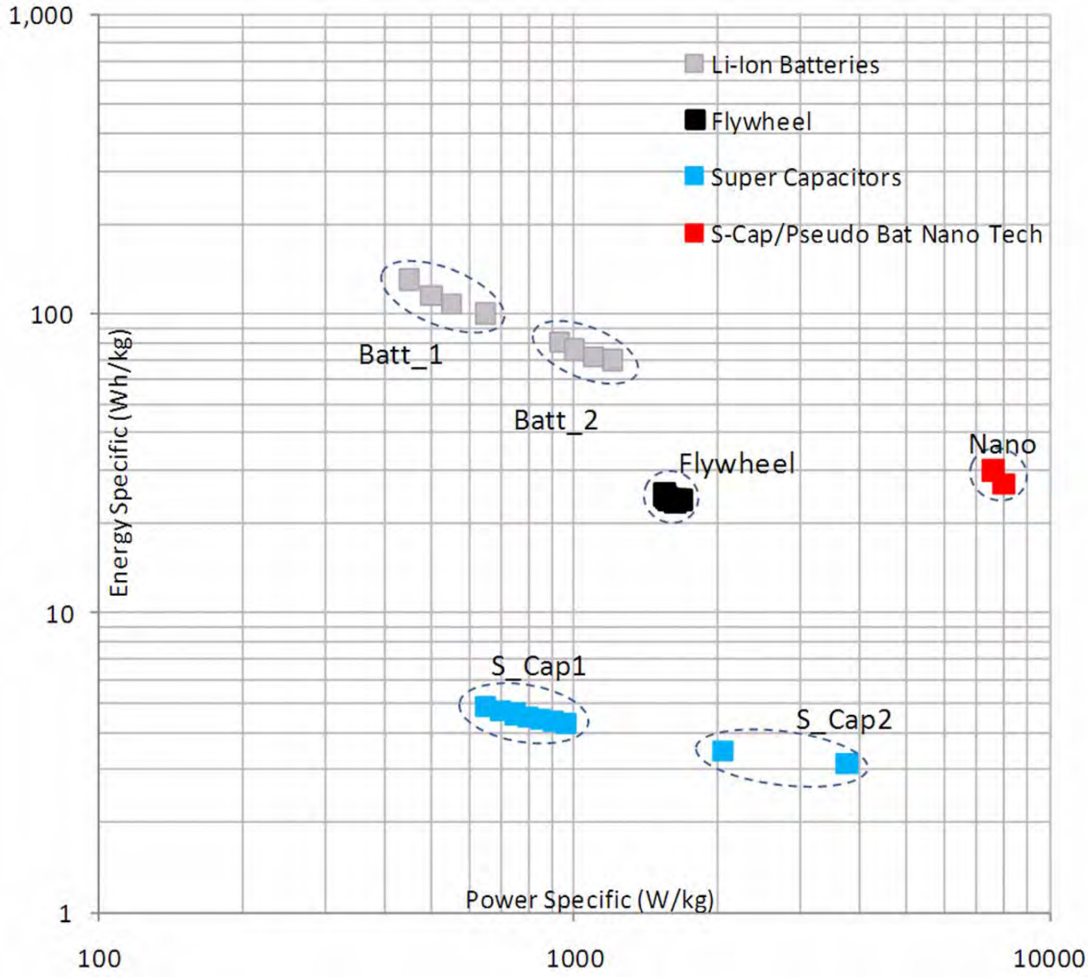


Figure 25 - Ragon plot of storage devices used in the modelling

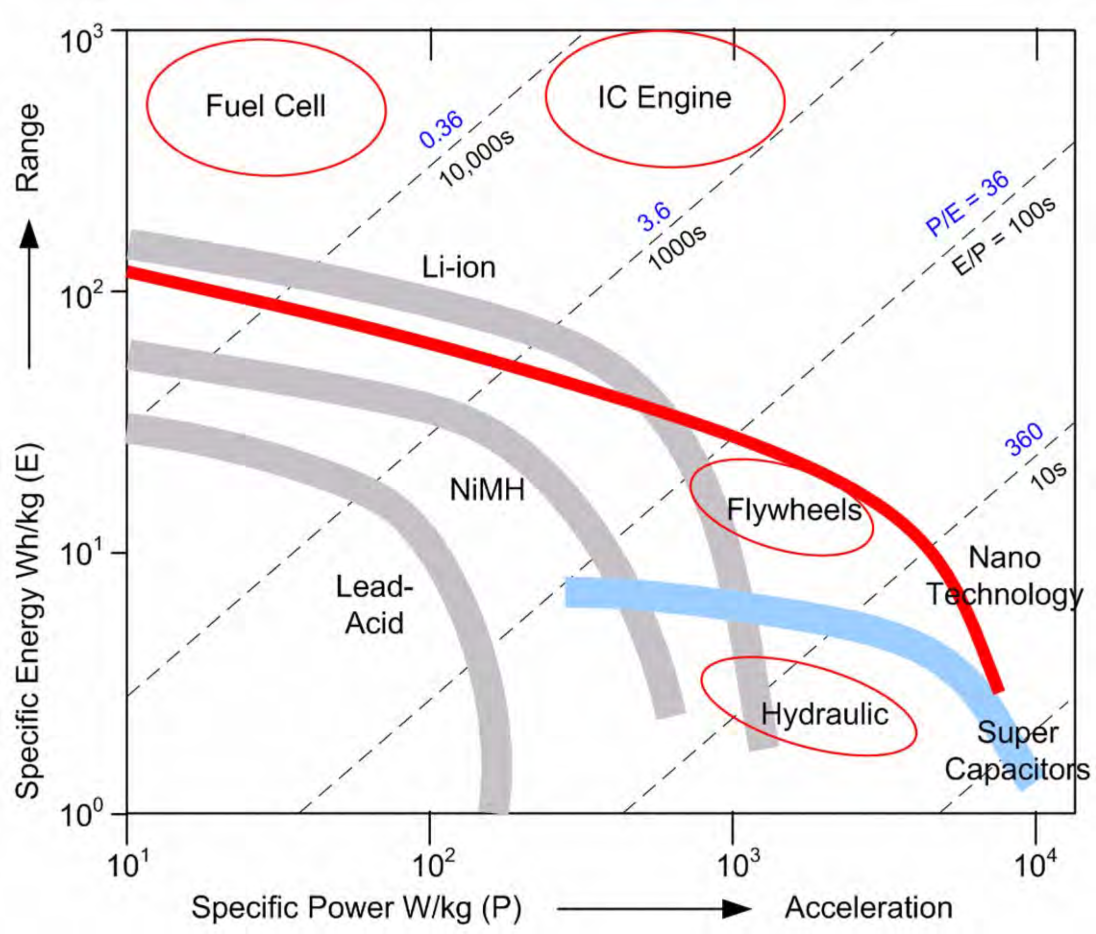


Figure 26 - Ragon plot of existing storage devices in the market

12.4 Control Strategies

The performance of the storage device is governed by the control strategies of the energy management system. For this purpose, four different control strategies have been employed in the modelling (though one of these has not been implemented as it depends on the route detail). These are described below:

1. A control strategy that maintains maximum stored charge all the time. This strategy is suitable for operating through gaps in the OHL. The controller scheme is shown in Figure 27. The braking characteristic (black) is maintained when the train is operating under the wire or within gaps. The motoring characteristic (blue) is maintained when the train

operates within gaps. Under the wire the storage device is continuously charged up following the (red) characteristic.

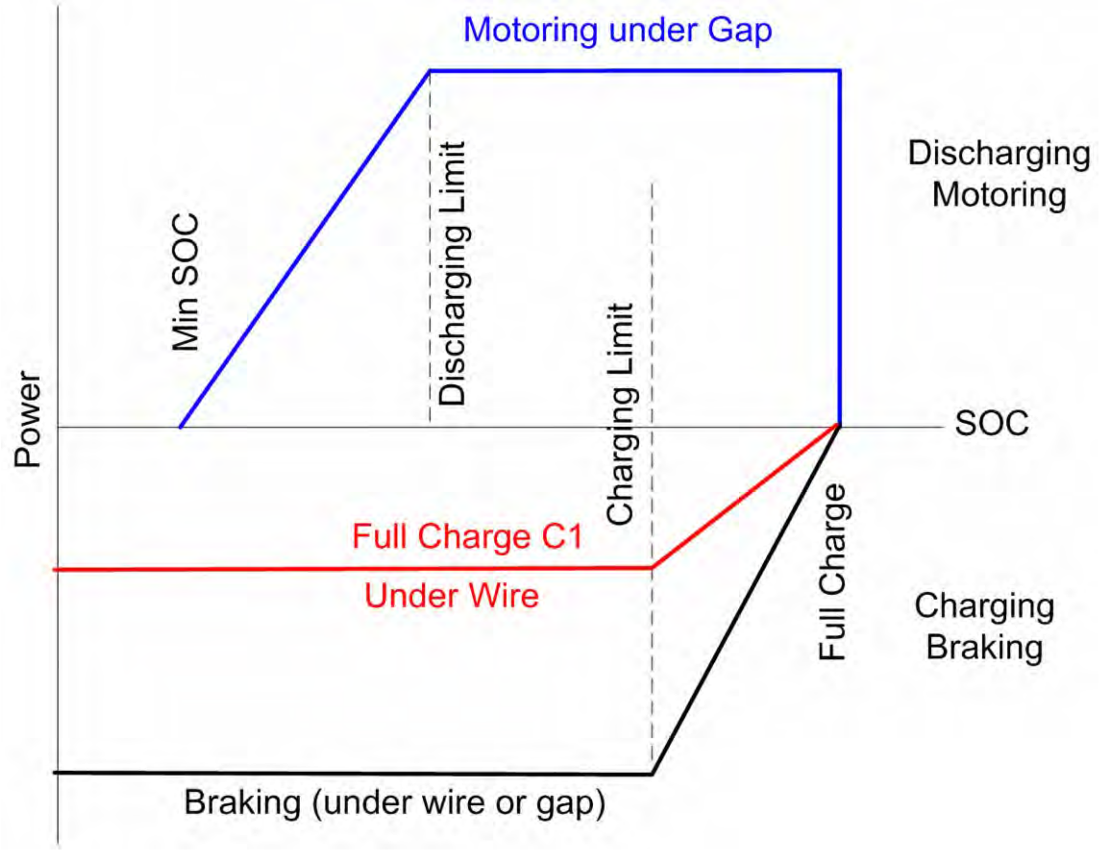


Figure 27 - **Control strategy that maintains maximum charge all the time**

2 A control strategy that maintains minimum charge all the time. This strategy is suitable to recover maximum braking energy. The controller scheme is shown Figure 28. The braking characteristic (black) is maintained when the train is operating under the wire or within gaps. The motoring characteristic (blue) is maintained when the train operates within gaps. Under the wire the storage device is continuously discharged following the (red) characteristic.

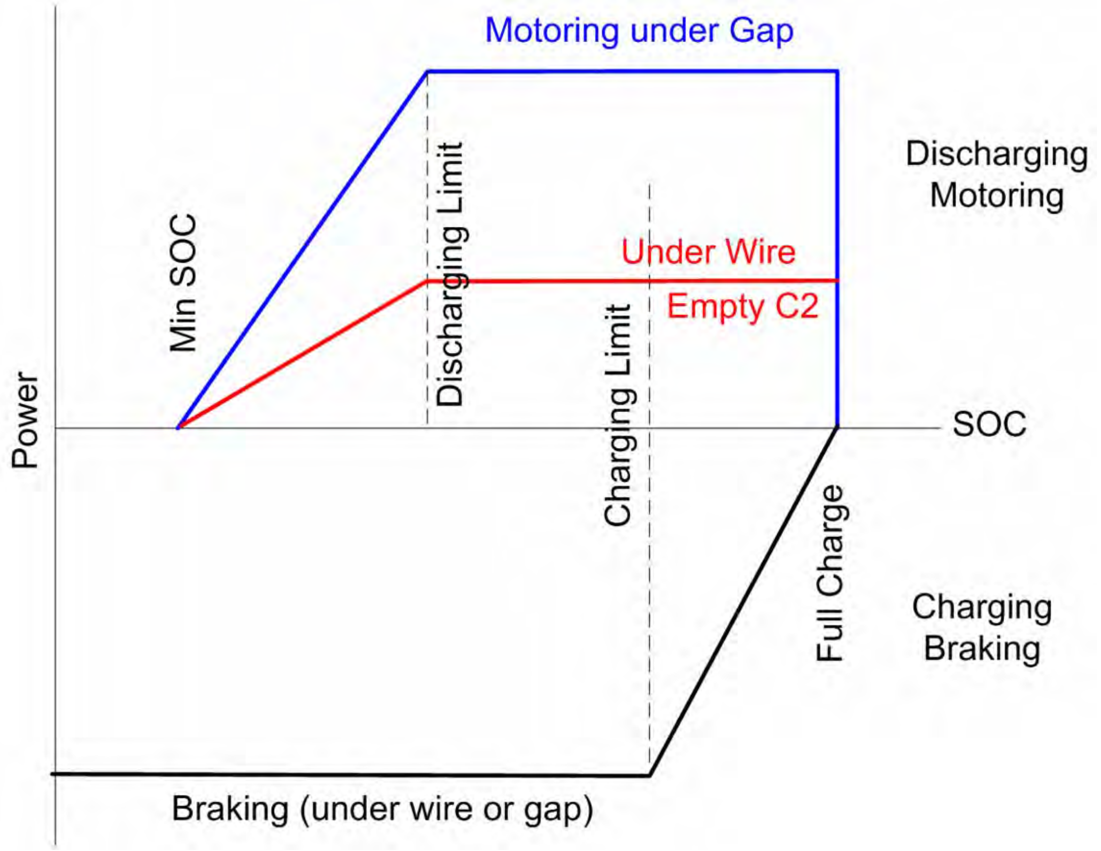


Figure 28 - Control strategy that maintains minimum charge all the time

3 A control strategy where the energy stored is dynamically regulated by the speed. This strategy is suitable for both, operating within gaps and to recover maximum braking energy. The controller minimises the energy stored at high speeds to enable capturing maximum regenerative braking. On the other hand the energy stored is maximised at low speeds in order to power the train through a gap, should it be encountered. The controller strategy scheme is shown in Figure 29. The braking characteristic (black) is maintained when the train is operating under the wire or within gaps. The motoring characteristic (blue) is maintained when the train operates within gaps. Under the wire the storage device is continuously charged, or discharged, depending on the train speed as shown by the (red) zone characteristics.

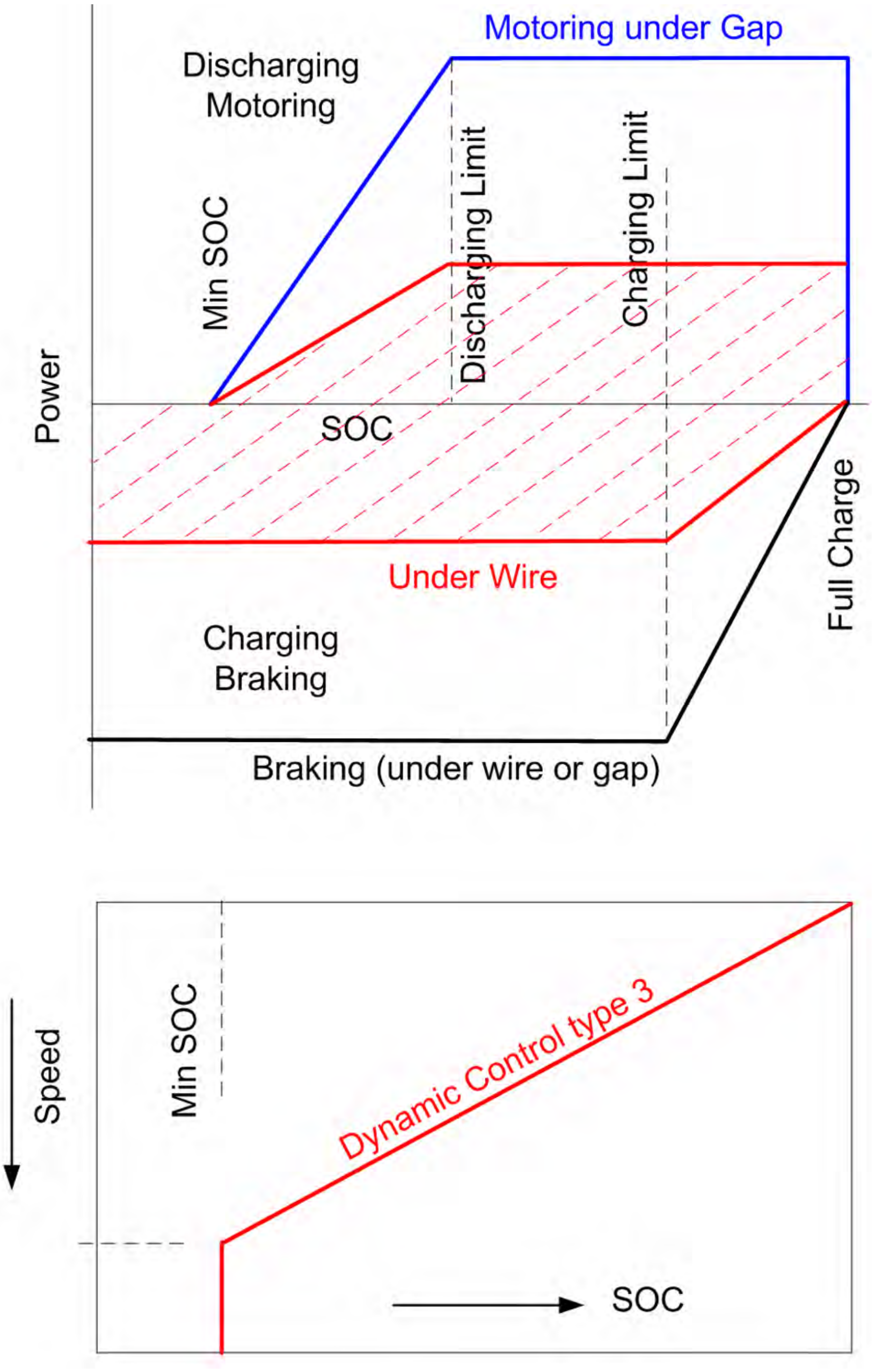


Figure 29 - A speed dependent control strategy

The charging, or discharging, current can be evaluated as the integration over time of the rate of variation of the State Of Charge (SOC), which is a function of the speed. This relationship may be expressed in the formula:

$$Storage\ Device\ Current = \int_{Time} \Delta SOC\ (\ Speed\ )$$

The integration on the right hand side of the equation is a subject of detailed analysis to optimise the controller performance. The integration can be designed to compensate for instabilities, or overshoots, that could occur during transients. This effect has been analysed by considering the complete control system block diagram as shown in Figure 30.

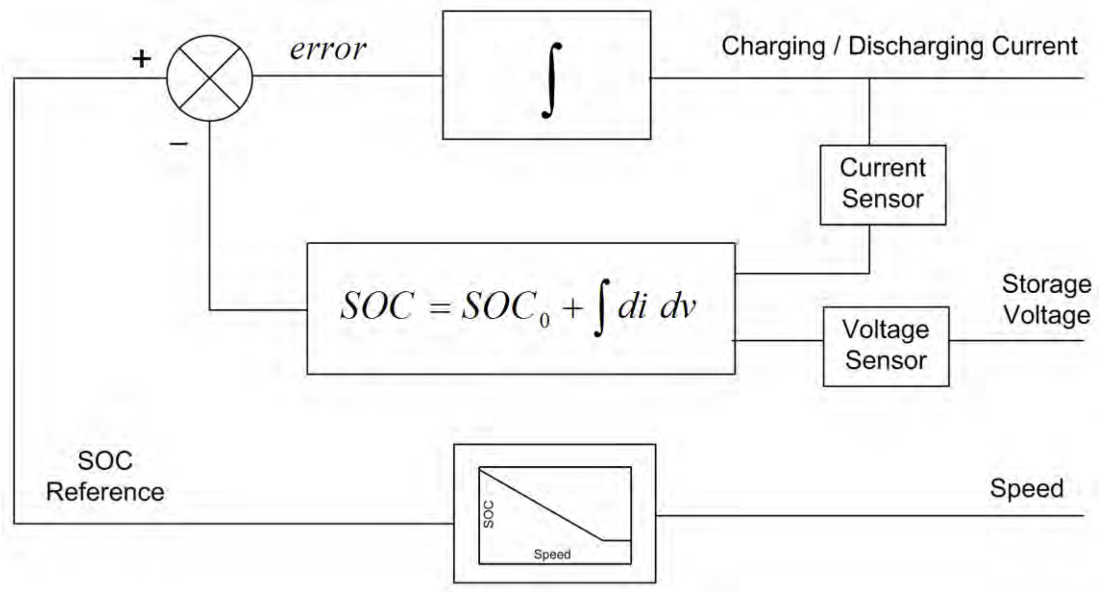


Figure 30 - Block diagram of the controller type 3

The compensation of the integrator must include a pole-zero compensation that can be expressed in the analogue from by the formula:

$$T = \frac{s + a}{bs}$$

However, since the simulation, and most likely a full scale modern controller, is based on digitisation based on a specific sampling rate, then the digitised form of the previous equation may be expressed as:

$$I(n) = I(n-1) + \eta[e(n) + \beta(n-1)], \text{ where } \eta = \frac{1}{b(ar/2+1)} \text{ and } \beta = \frac{ar/2-1}{ar/2+1}$$

Were b is gain, a is the compensation pole effect and r is the sampling rate. I is the charging, or discharging, current.

4 A control strategy based on a 'Look Ahead' algorithm: this has not been implemented since it is route dependent. The technique is based on incorporating the route details within the control strategy of the storage device. This will enable anticipating the motoring or braking requirements ahead, hence its name. The technique could be relatively simple. For example, maintaining maximum energy if a gap is ahead and minimum energy when braking is expected. Combining of both gaps and braking can also be accommodated for relatively easily. It should be noted that train onboard controllers are increasingly being introduced recently to optimise operation, e.g. eco-driving, train regulation, traffic management, etc. Integrating a storage device controller would not be too difficult to achieve using this technology.

12.5 Infrastructures and Operation

The infrastructures information incorporates details of the route. The minimum infrastructures information required are track gradient, speed limits, curvatures, station locations, tunnel sections, OHL gaps and coasting points. An example is shown in Figure 31 using assumed infrastructures data. Note this example has been used for testing purposes. It contains some irregular intervals, spacing, etc. the purpose of which is to push the simulation algorithms to the limit for testing purposes. The format of the data is described in reference 3.

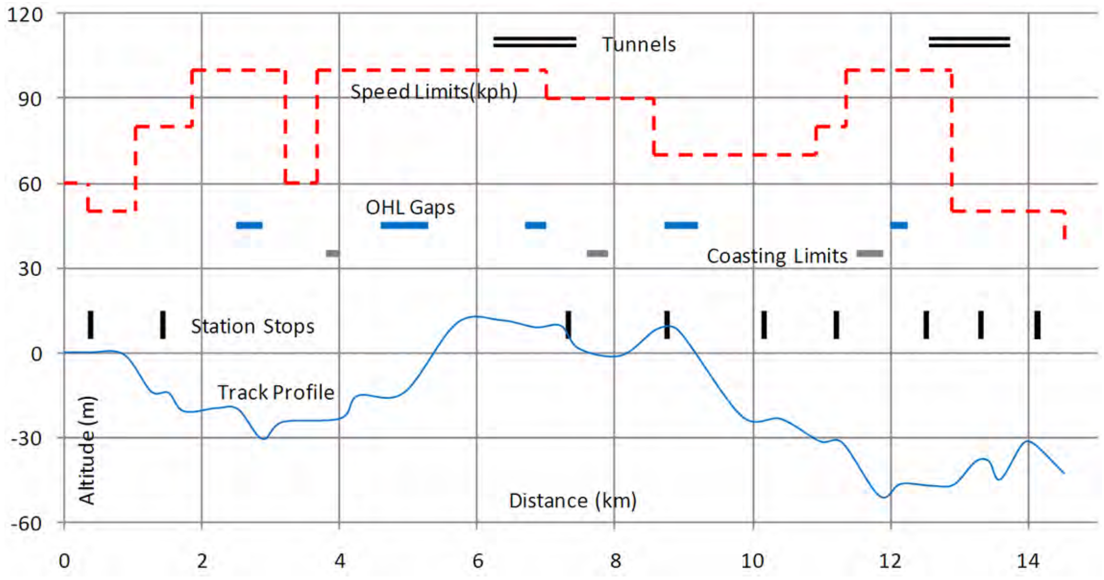


Figure 31 - Example of infrastructures data

To be able to handle the infrastructures' data, the convention shown in Figure 32 is used. The route mileage points are used to show the existence, or change of, infrastructure parameters. As such, at any location along the route the corresponding gradient, speed limit, tunnel or open section, OHL gaps, coasting points, stopping approaches and curvatures are known to the train. As the simulation is carried out using constant time sampling steps, the results obtained are in the form of time-distance-speed for the entire run time specified.

The simulation is based on setting a continuously changing target speed for the train at any moment in time. The actual speed of the train is determined by setting an appropriate acceleration rate that attempts to achieve the target speed. In the event the available torque is smaller than the required torque the speed drops below the target speed. Clearly, if the supply is unavailable, in cases of operating within a gap or coasting, there will be no torque available and as such a deceleration will occur. The rate of deceleration is determined by speed, gradient and train mass and resistance. Deceleration also takes place at stops and/or speed limit approaches.

There are also constraints on speed transitions during both motoring and braking. This is regulated by introducing jerk limits which are defined as the rate of change of acceleration, or deceleration. Refer to Figure 33 and the following three equations for speed, acceleration and jerk limits specification.

Speed is rate of change of distance

$$V = \frac{dS}{dt}$$

Acceleration is rate of change of speed

$$a = \frac{dV}{dt}$$

Jerk is rate of change acceleration

$$j = \frac{da}{dt}$$

The speed profile is calculated for three cases, ideal profile for signalling purposes, speed profile when the train is fed from the supply and a speed profile when OHL gaps exist.

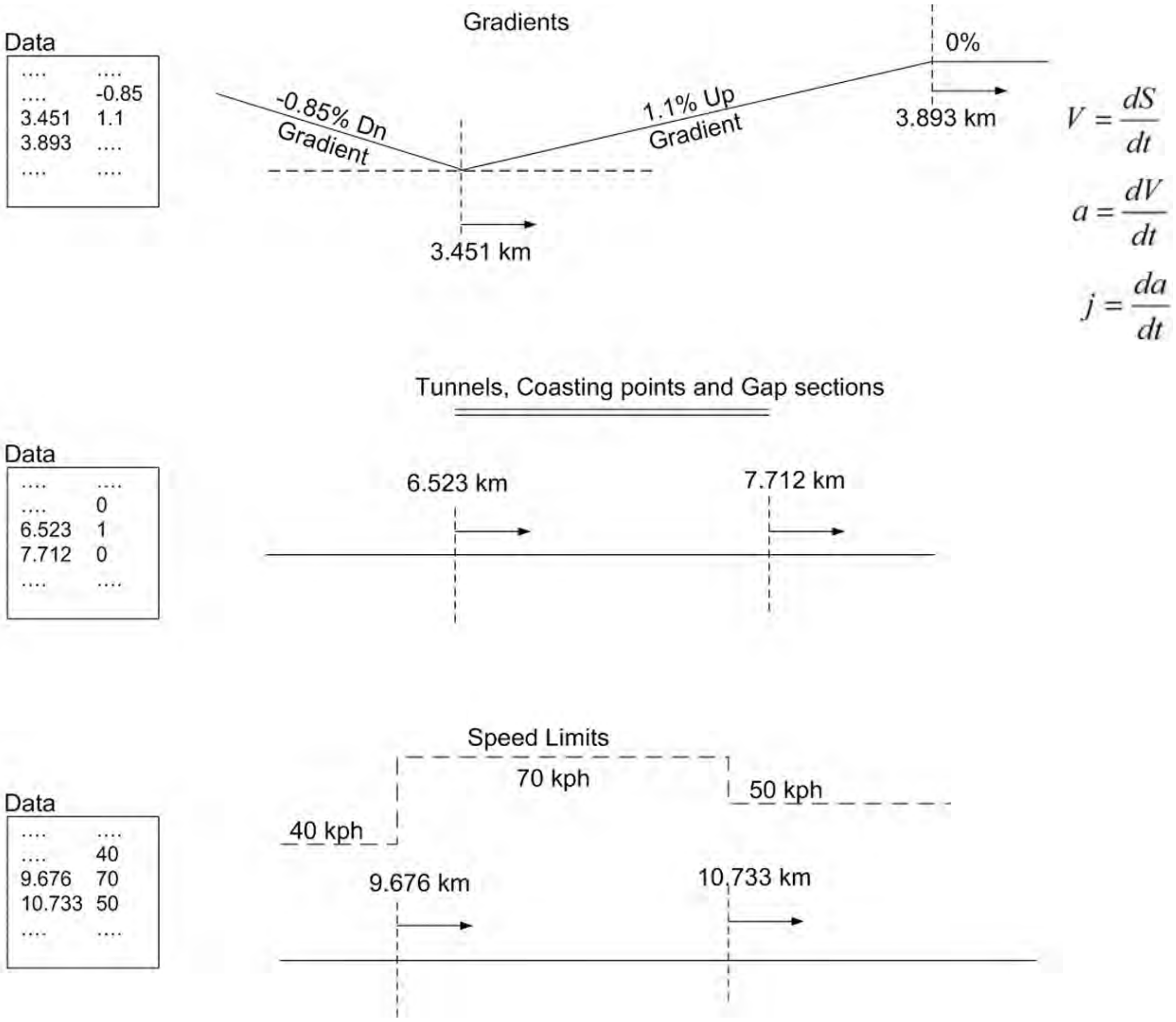


Figure 32 - Infrastructures convention

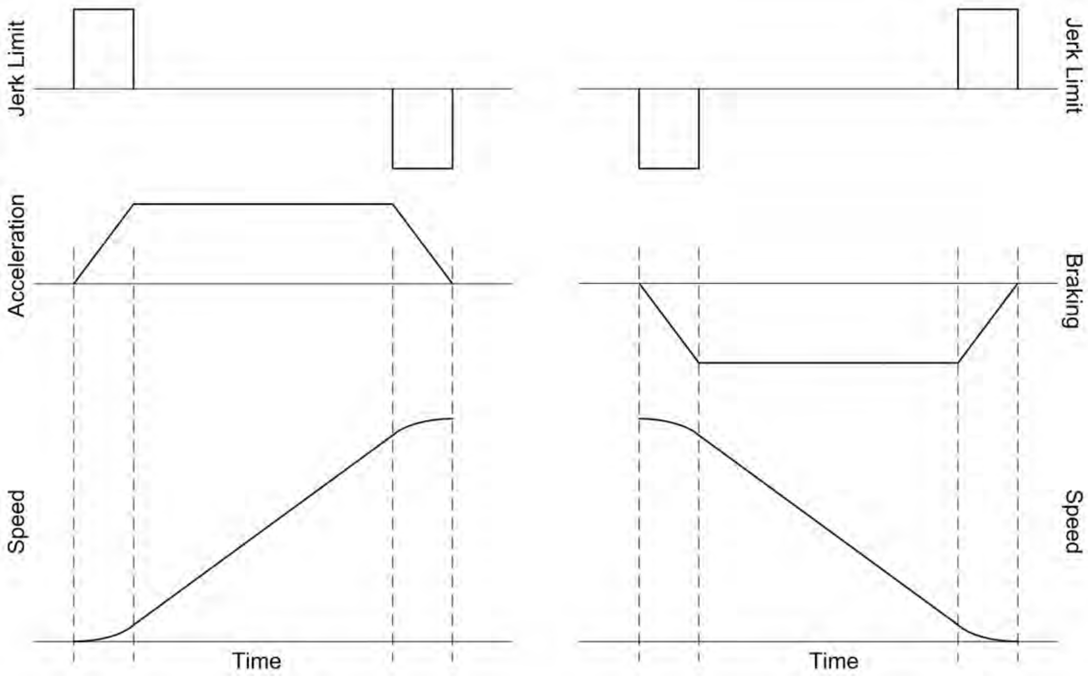


Figure 33 - Jerks and acceleration rates during motoring and braking

13 Appendix: Selected Rail Applications

This Appendix contains information about some of the known rail applications of energy storage systems. It covers mainly systems built by Bombardier and Siemens. Other devices are also assessed in lesser detail.

Bombardier has developed the MITRAC energy saver designed for a use aboard light rail vehicles (LRV) with the main objective of energy recovery. A vehicle prototype of the Mannheim public transport operator MVV has completed since September 2003 four years of trial in passenger operation. Long term results showed that the tram's traction power consumption was reduced by 30% and the overall power needs including doors, air-conditioning and lighting were cut by a total of 20%. During testing the 1 kW/h unit enabled the vehicle to run with its pantograph lowered over 500 metres. The savings come mainly from the recovery of the kinetic energy of the vehicle when braking. This energy is converted into electrical energy by the motor/generator, sent to the dc link via the traction inverter and stored in the on-board super capacitor banks. The long-term reliability of the technology has been demonstrated and the device has now been removed for an assessment of how production trams will have the roof-mounted equipment integrated into the vehicle design. Seeing the results, MVV has decided to include MITRAC energy saver on 19 trams ordered in October 2007. They have been ordered at the instigation of the city of Heidelberg, which wishes to avoid erecting wires through the planned extension of the university campus. The city expects that the additional 270.000€ cost per vehicle will be recovered over the first 15 years of the vehicle life. According to Bombardier, negotiations are now underway with other operators.

The MITRAC energy saver is made up of some 300 MAXWELL super capacitor cells. MITRAC specifications:

- Maximum power 300 kW
- Installed energy 0.850 kWh
- Weight 477 kg
- Dimensions 100 X 950 X 455 mm
- Cooling forced air

Bombardier is also developing other applications for the MITRAC energy saver such as peak power units in diesel multiple units.

Siemens has developed two types of energy storage systems for rail vehicles:

- SITRAS stationary system
- SIBAC on-board system

The SITRAS SES (Static Energy Storage) consists in a bank of super capacitors (3000 Farads and 2.7V) installed at some points of the network to recover the energy of the vehicles operating on the line and to stabilize the voltage at weak points. The system is composed by super capacitors interconnected and mounted in a massive shelf located either at the substation level, in parallel with the power supply, or at critical points such as end of lines where voltage drops are prone to occur. The system is in full time service in many cities including Bochum, Cologne and Dresden (Germany), Madrid (Spain), Peking (China).

SITRAS specifications:

Voltage	Vdc	600	750
Number of cells		1,050	1,344
Capacitance	F	103	80
Usable energy	kWh	1.7	2.5
Max energy saving	kWh/h	50	80
Peak power	MW	1	1
Auxiliary supply		3-phase 416V	3-phase 416V
Temperature	C^o	-20 to 40	-20 to 40
Dimensions	m	1.4 X 0.9 X 0.7	1.4 X 0.9 X 0.7
Weight	tonne	4	4.3

In Cologne, the system is used in energy-saving mode. A reduction of 40kWh/h in primary power consumption has been observed, resulting in 320.000 kWh saved annually. Depending on the circumstances, a maximum of 500.000 kWh could be saved annually by using a single system and potential emissions reductions of 300 CO_2 tonnes are expected on a yearly basis.

In Madrid's metro, the main goal of the system is to stabilize the network voltage. Voltage drops occur when several vehicles accelerate simultaneously. In such a scenario, a high demand of current takes and causes a voltage drop that may fall below critical boundaries and cause disruptions. The principle of the SITRAS system is, in this case, to provide energy to the vehicles accelerating when the network voltage falls below a predefined level. After the acceleration, the system is recharged either slowly from the network or fast during a vehicle deceleration. Voltage stability was significantly improved where voltages below 490 V do not occur anymore and the frequency of voltages under 530 V is considerably reduced.

Siemens have also developed the SIBAC energy storage system for on-board applications. The expected energy savings is ranging from 20% up to 35%, but the system is still at the prototype stage and is, as far as currently known, not used in any city yet. The prototype has already been tested and a reference approval for the usage of the system on tramways has been issued.

SIBAC specifications:

Voltage (Vdc)	360 to 670
Usable energy (kWh)	0.6
Max power (kW)	300
Continuous power (kW)	100
Dimensions (mm)	1,850 X 1,610 X 550
Cooling	Forced air

Alstom has developed and tested in real operating conditions, in partnership with the Dutch Research and Development Company CCM (Centre for Concepts in Mechatronics), a flywheel system for its CITADIS tram in Rotterdam. This system is composed by a carbon fibred rotating permanent magnet motor-generator located on the roof of the tram, which works on the same principle as a spinning top. The kinetic energy stored during braking is restored by the electric generator to the propulsion system the next time the tramway accelerates. The system is recharged each time the vehicle brakes or by a complementary high-speed recharging system each time the tramway stops at a station. Alstom expects a lifetime of some 30 years for its system.

The Alstom is also currently testing a super capacitor energy storage device on Paris Metro designed to recover braking energy and has a capacity of 2.2kWh and is built using Maxwell super capacitors. It weighs 1.5 ton and installed on a 7-car train.

In GB, in the last two years Porterbrook Leasing Company Limited has been involved in a hybrid trial programme with Network Rail on the Hitachi Verification Train 2 (HVT-2) which is a modified diesel electric loco plus coaches, using ac motors instead of dc. This train has been hybridised and equipped with a one-ton 48kWh Hitachi Li-ion battery. The train is known as Hayabusa. However results from these trials are not available at the time of writing this report.

RSSB Research Programme
Block 2 Angel Square
1 Torrens Street
London
EC1V 1NY

research@rssb.co.uk

www.rssb.co.uk/research/pages/industryresearchprogramme.aspx

RESEARCH FOR A MOBILE FUTURE

DRESDEN

Energy-saving potential of energy storage systems in public transport networks

TROLLEY Summer University
Leipzig, 25th October 2012

Sven Klausner

Dipl.-Ing. (FH)

FRAUNHOFER INSTITUTE FOR TRANSPORTATION AND INFRASTRUCTURE SYSTEMS IVI

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Outline

- Energy-saving potential using the example of a modern tram
- Technical description of a supercapacitor-based energy storage system
- Network simulation model of the Fraunhofer IVI for electric vehicles with integrated energy storage system
- Calculation example: Trolleybus with energy storage system (BBG Eberswalde)
- Summary

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Energy-saving potential
Influencing factors

Variable vehicle configurations
Variable network conditions (track + power supply)
Variable operational requirement
Variable ambient conditions

- Vehicle equipment and performance
  - Level of motorization and facilities (heating, air conditioning)
  - Acceleration, speed, weight

Energy-saving potential
Influencing factors

Variable vehicle configurations
Variable network conditions (track + power supply)
Variable operational requirement
Variable ambient conditions

- Topography of rail track and network
  - Distance between stops, grade of track
  - Feeding sectors, coupling of trolley system

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Energy-saving potential
Influencing factors

Variable vehicle configurations
Variable network conditions (track + power supply)
Variable operational requirement
Variable ambient conditions

- Operational and schedule problems
  - Work and holiday traffic, weekend
  - Construction sites, maintenance

Energy-saving potential
Influencing factors

Variable vehicle configurations
Variable network conditions (track + power supply)
Variable operational requirement
Variable ambient conditions

- Ambient temperature AB1

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Folie 7

AB1 Könnten Sie hierzu noch einen Stichpunkt bringen, damit alle Einflussfaktoren abgehandelt werden?

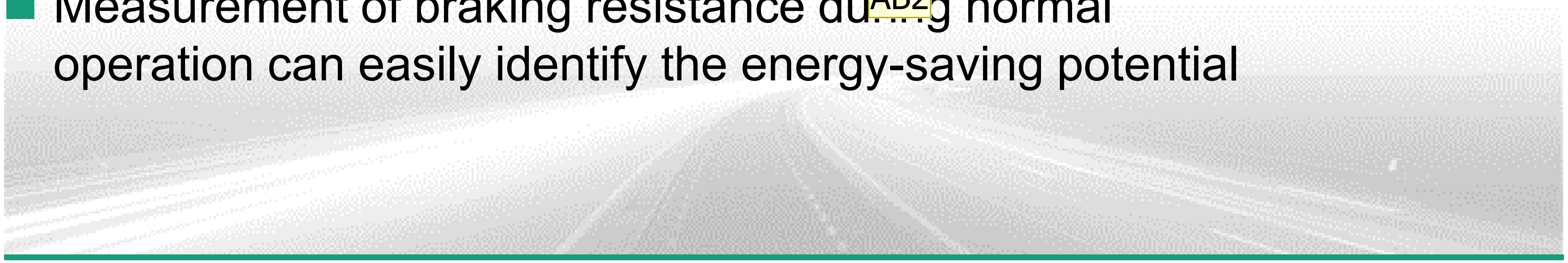
Adler, Bettina; 10.10.2012

Energy-saving potential

Influencing factors

Variable vehicle configurations
Variable network conditions (track + power supply)
Variable operational requirement
Variable ambient conditions

- Network simulations have to consider a multitude of influencing factors
- Measurement of braking resistance during normal operation can easily identify the energy-saving potential



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Folie 8

AB2 oder ist unused breaking energy im Englischen besser für Bremswiderstand?

Adler, Bettina; 10.10.2012

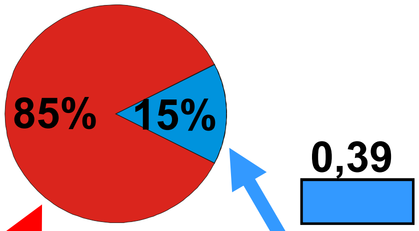
Energy-saving potential
Measurement

- Field experiment over a period of 9 months
- 45-m tram without air conditioning for the compartement (NGTD12)
- Normal vehicle operation
- Measurement equipment without intervention in the vehicle control system
- Current and voltage measurement with high local and temporal resolution (5 Hz, GPS)
- Comprehensive software tools for data processing and analysis

Source: DVB AG

Visualization of measurement data – velocity
(Source of backround picture: GoogleEarth)

Energy-saving potential
Results

	Urban centre
Winter T ≤ 5°C	

Energy into the braking resistors (E_{BR} / distance) in kWh/km

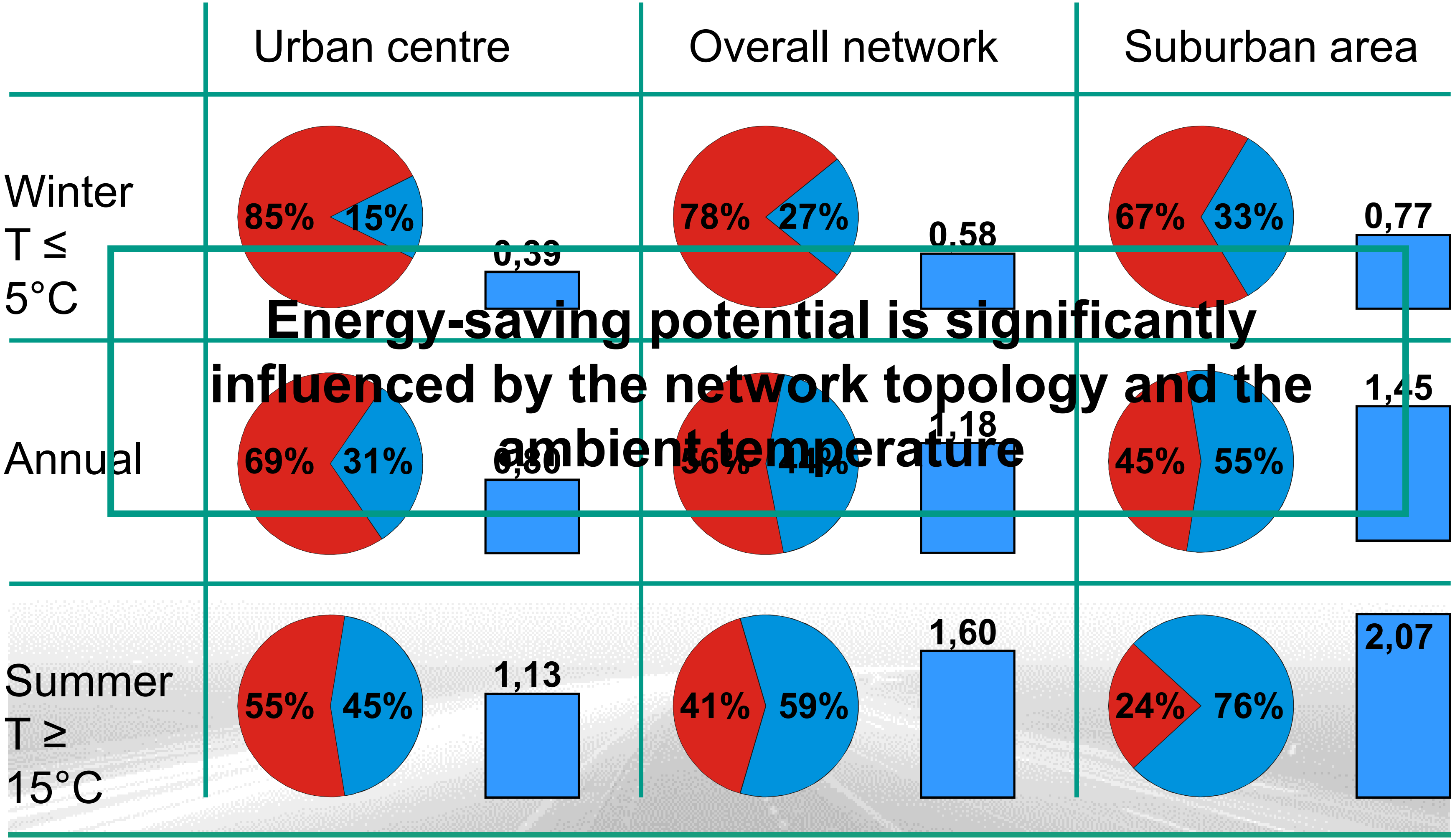
Used braking energy (vevicle + network): $(E_{M,AUX} + E_{M,OL}) / E_{M-}$

Energy into the braking resistors : $E_{M,BR} / E_{M-}$

relating to the available braking energy from the propulsion motors

BR – braking resistor
OL – overhead line
M – propulsion motor
AUX – auxilliary consumer

Energy-saving potential
Results



Energy-saving potential is significantly influenced by the network topology and the ambient temperature

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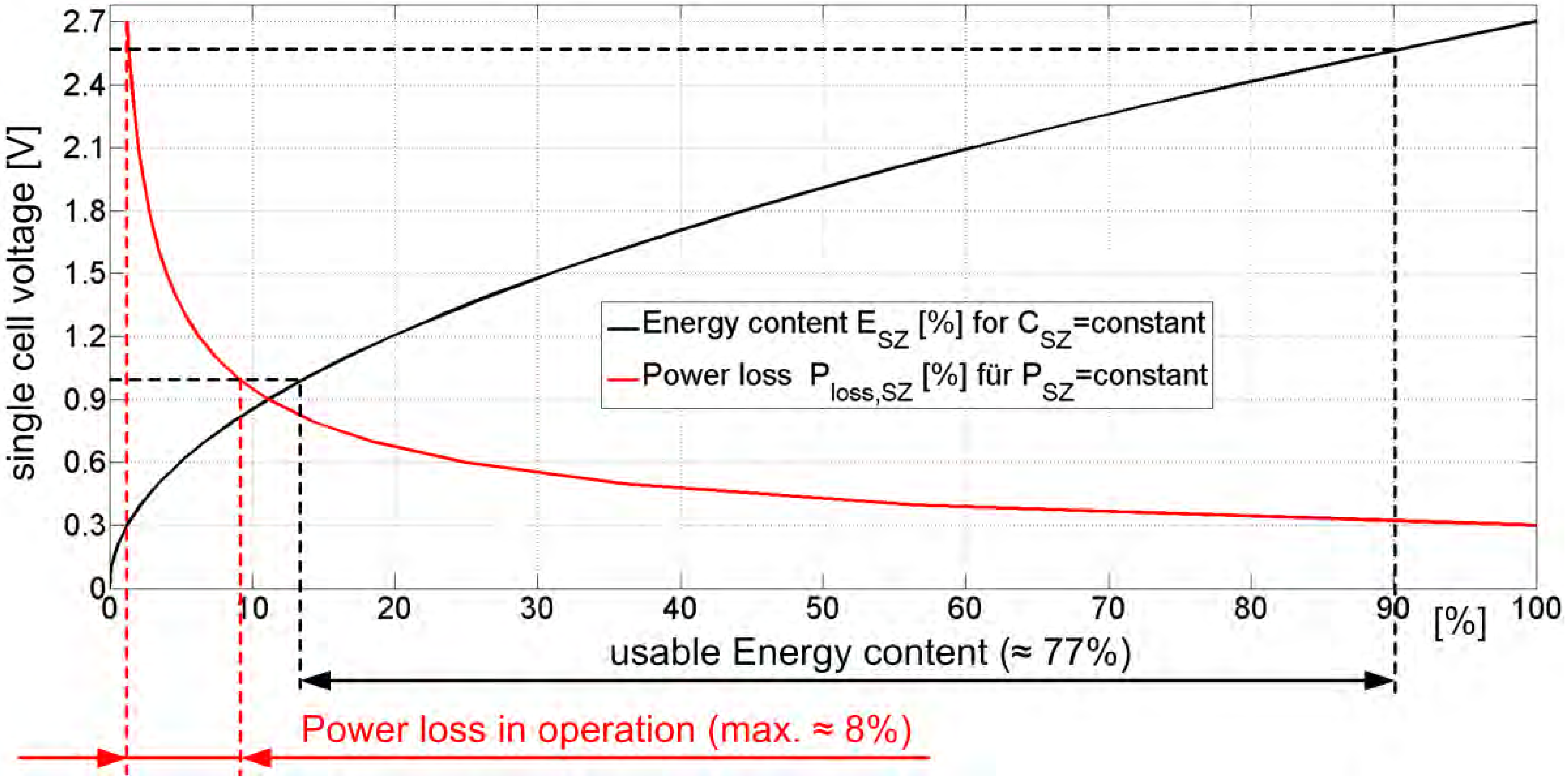
SCAP
Single cell

Source: Maxwell

- Cathode and anode filament wound
- Electrostatic energy storage
  →high economic lifetime
- Low energy density in comparison with batteries
  →Improvement by factor 2 in the last 10 years
  →Integration into a public transport vehicle possible
- Operational voltage range (typical) 1,0…2,55 V

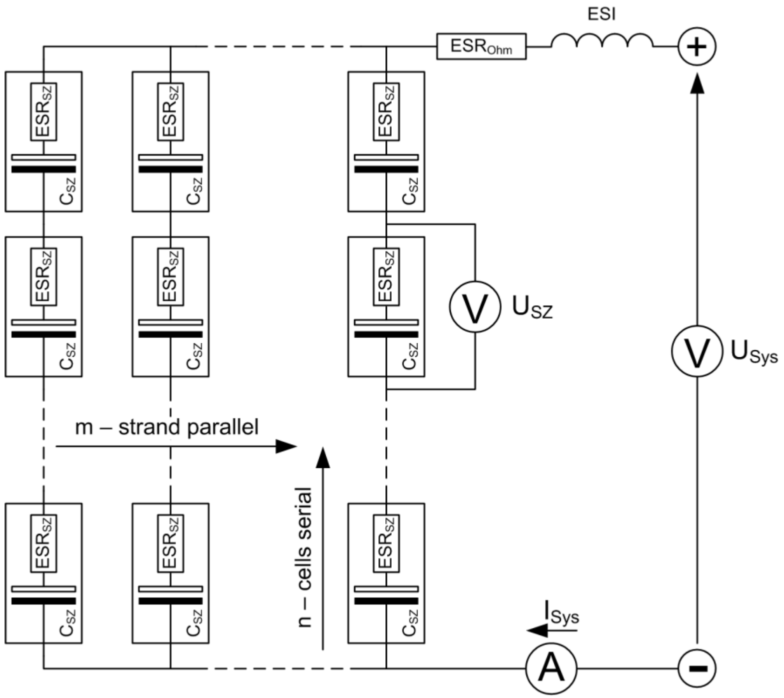
SCAP

Single cell



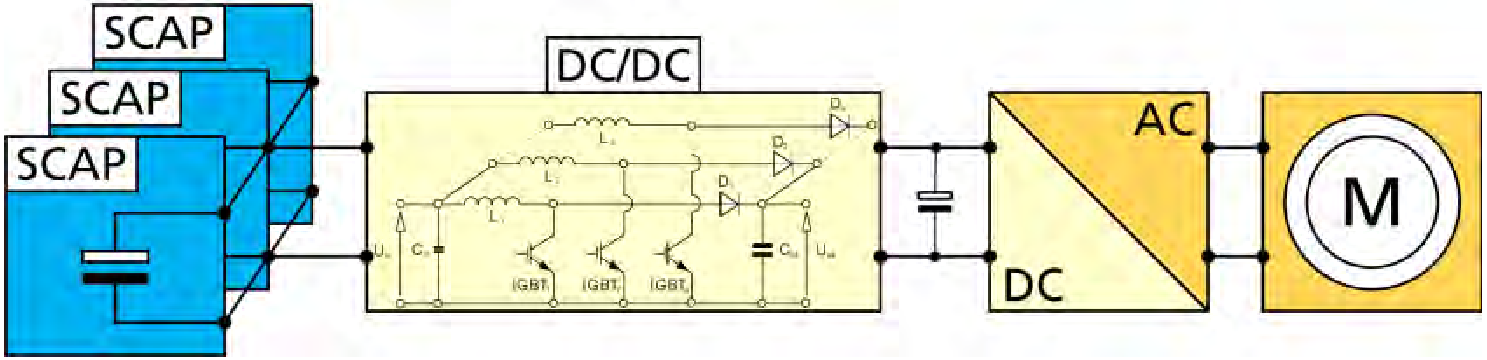
SCAP
Storage system

- Serial coupling of single cells range of several 100V
- Parallel coupling of cell strand →Increase of energy content
- Single cell monitoring (voltage) and module control (temperature)
- Cell voltage balancing not suitable for dynamic operation
- Mostly convective cooling/ventilation → liquid cooling unusual



SCAP

Power electronic coupling



- Selection of operational voltage range is a question of efficiency optimization
  - High operational voltage favorable (P_{loss} ⇩ for P=constant)
  - Effort for power electronic is dependent on the DC link voltage
  - Higher power losses caused by additional passive components
- Not only air cooling but also liquid cooling (water/glycol) usable for power electronic

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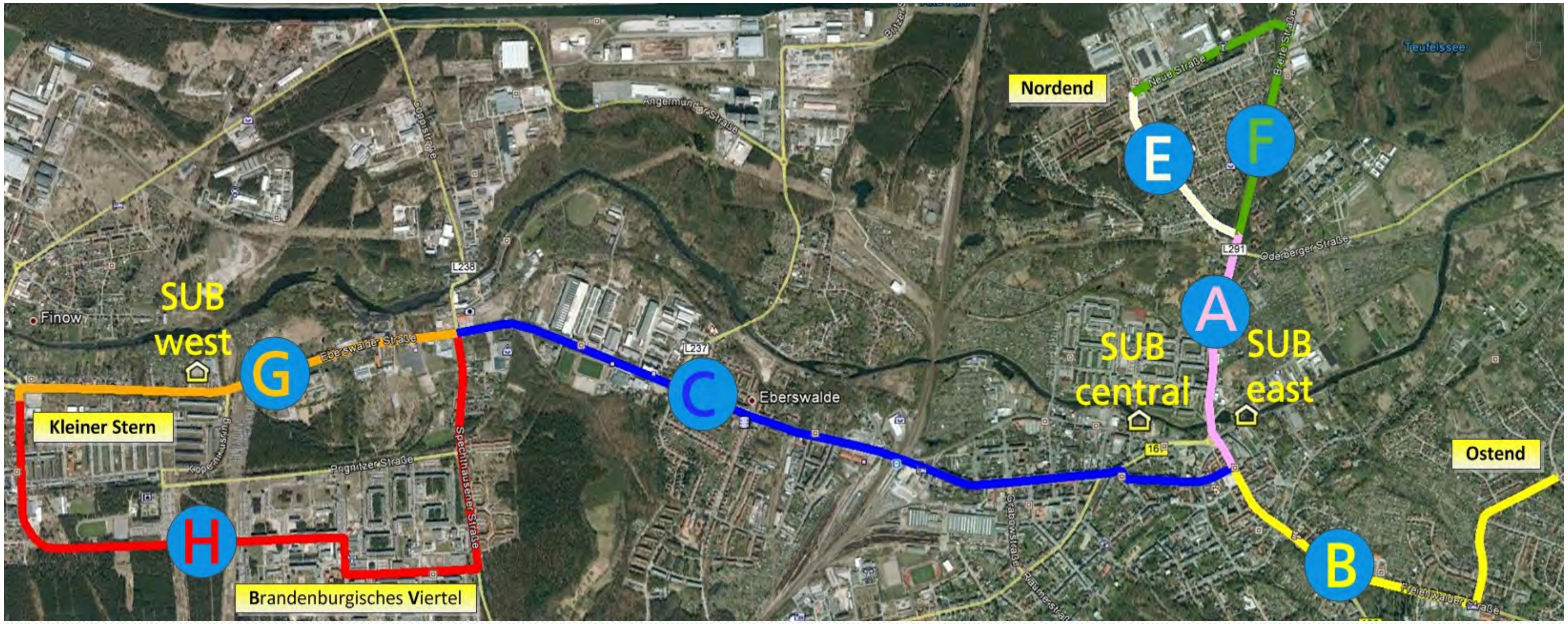
Network simulation model

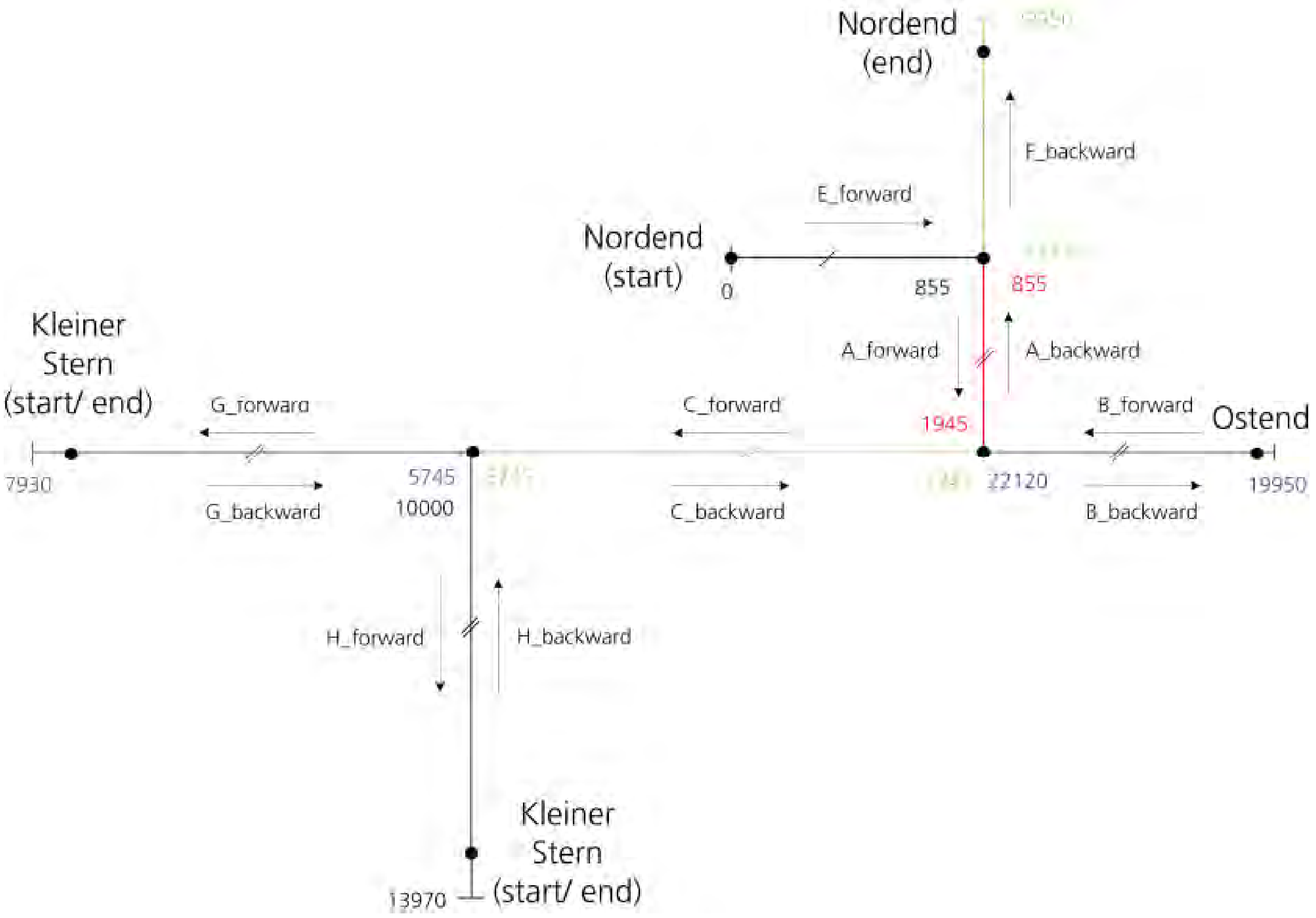
Trolley system, physical



Source : Google

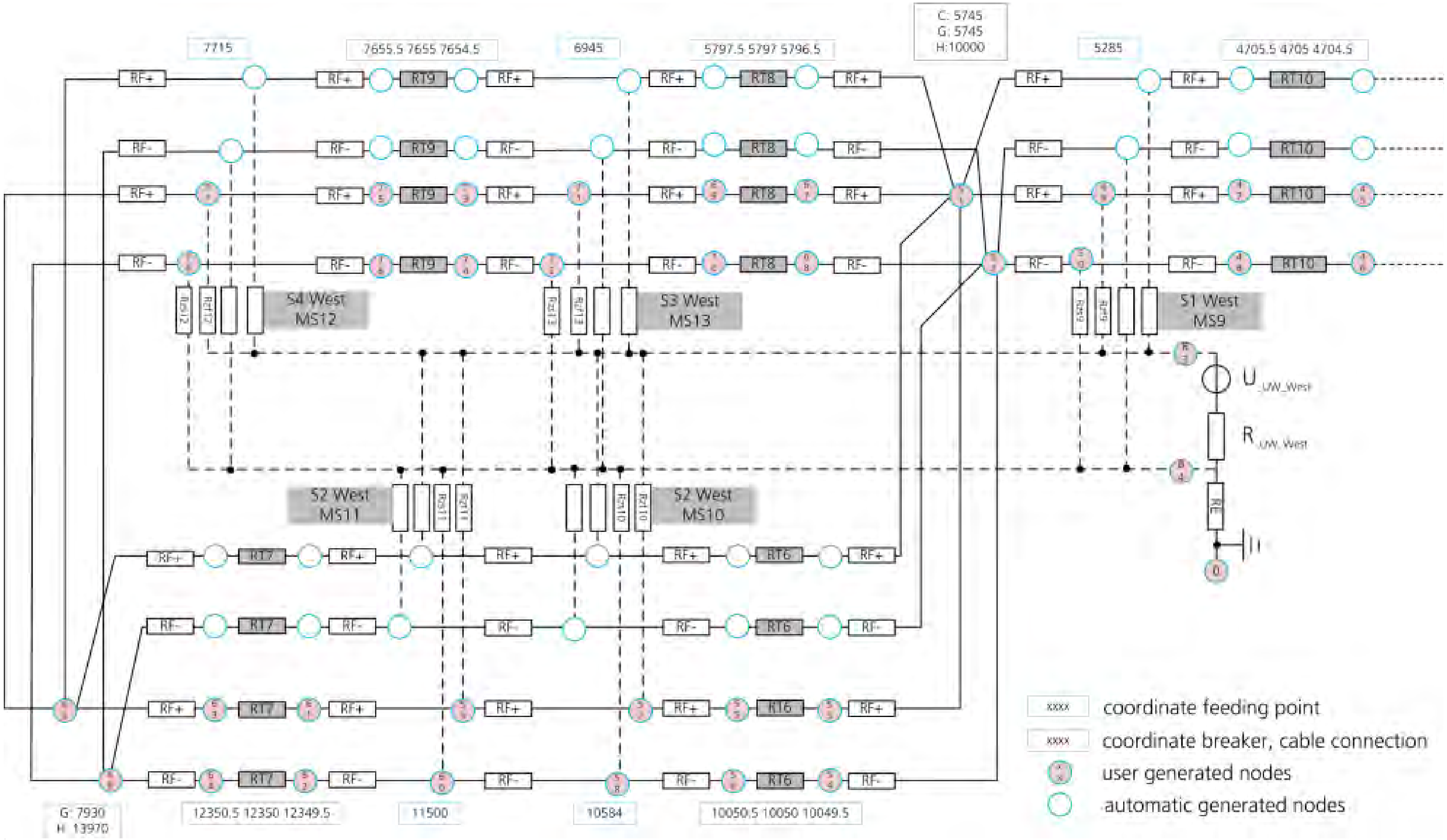
- Three rectifier substations
- Not illustrated: powered sections, input leads, couplings, breaker

Network simulation model
»Kilometrage«



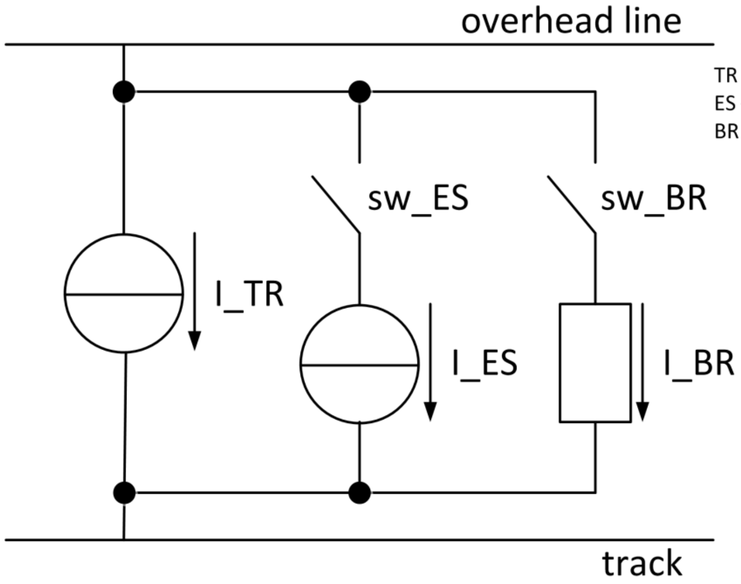
Network simulation model

Trolley system, modelled



Network simulation model

Vehicle model

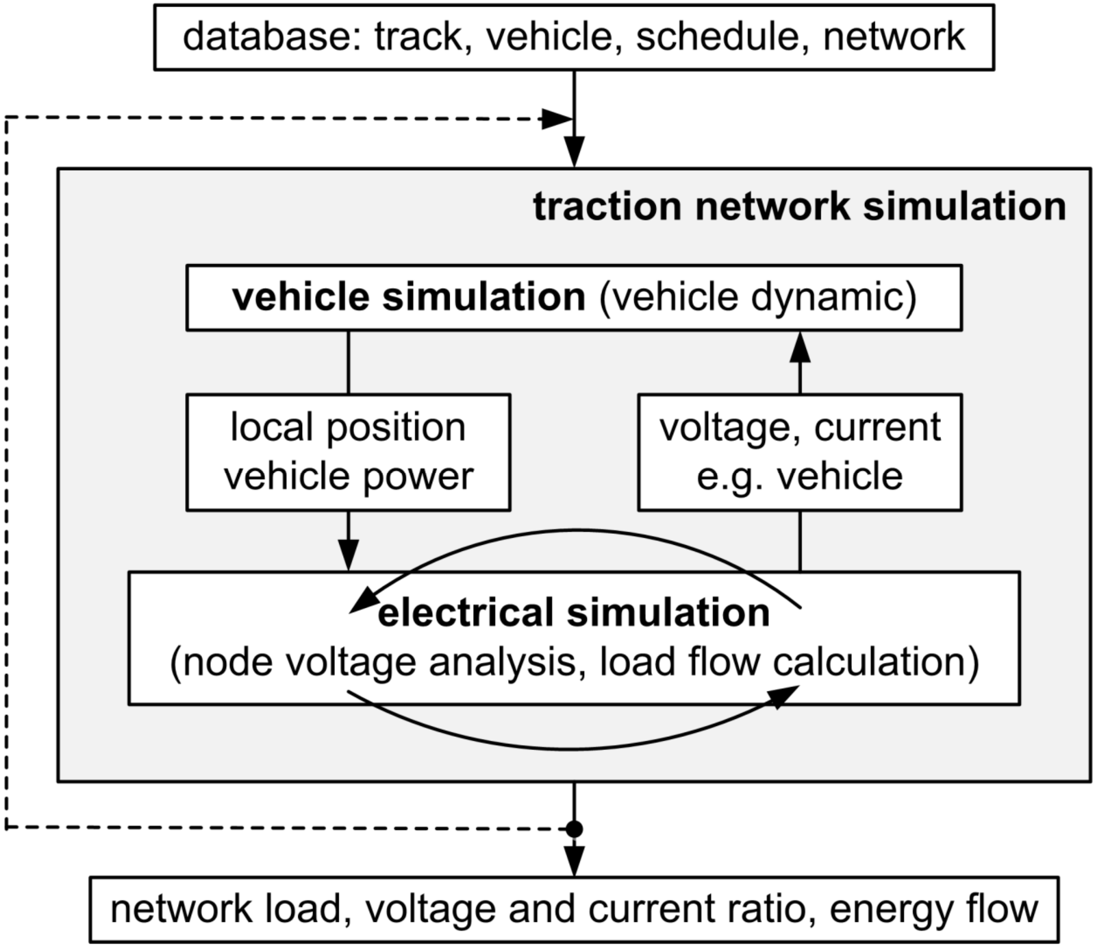


TR – traction vehicle
ES – energy storage system
BR – braking resistor

- Switched model
- Power consumption from overhead line → current source Power dissipation → voltage source
- Participation of energy storage system by control strategy
  Participation of braking resistor above specified voltage level

Network simulation model

Program sequence



database: track, vehicle, schedule, network

traction network simulation

vehicle simulation (vehicle dynamic)

local position
vehicle power

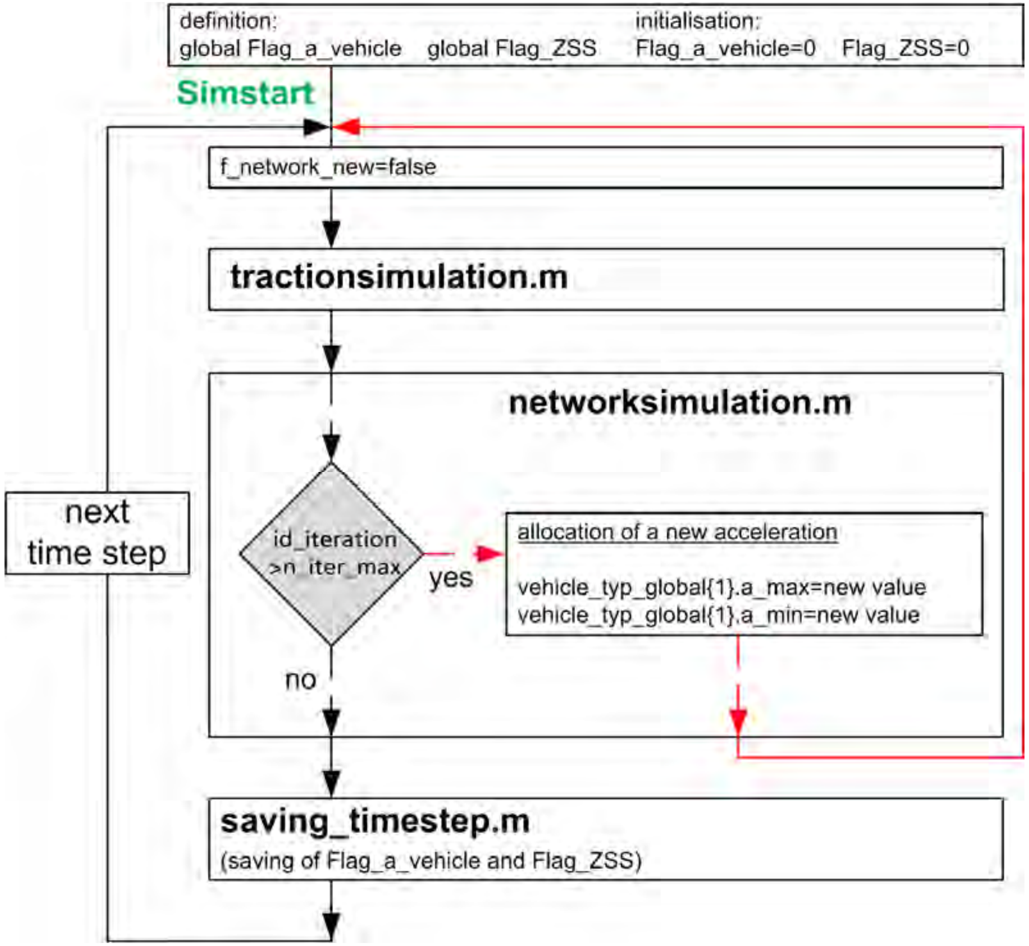
voltage, current
e.g. vehicle

electrical simulation
(node voltage analysis, load flow calculation)

network load, voltage and current ratio, energy flow

Network simulation model

Example: reduced power



definition:
global Flag_a_vehicle global Flag_ZSS

initialisation:
Flag_a_vehicle=0 Flag_ZSS=0

Simstart

f_network_new=false

tractionsimulation.m

networksimulation.m

allocation of a new acceleration

vehicle_typ_global{1}.a_max=new value
vehicle_typ_global{1}.a_min=new value

saving_timestep.m
(saving of Flag_a_vehicle and Flag_ZSS)

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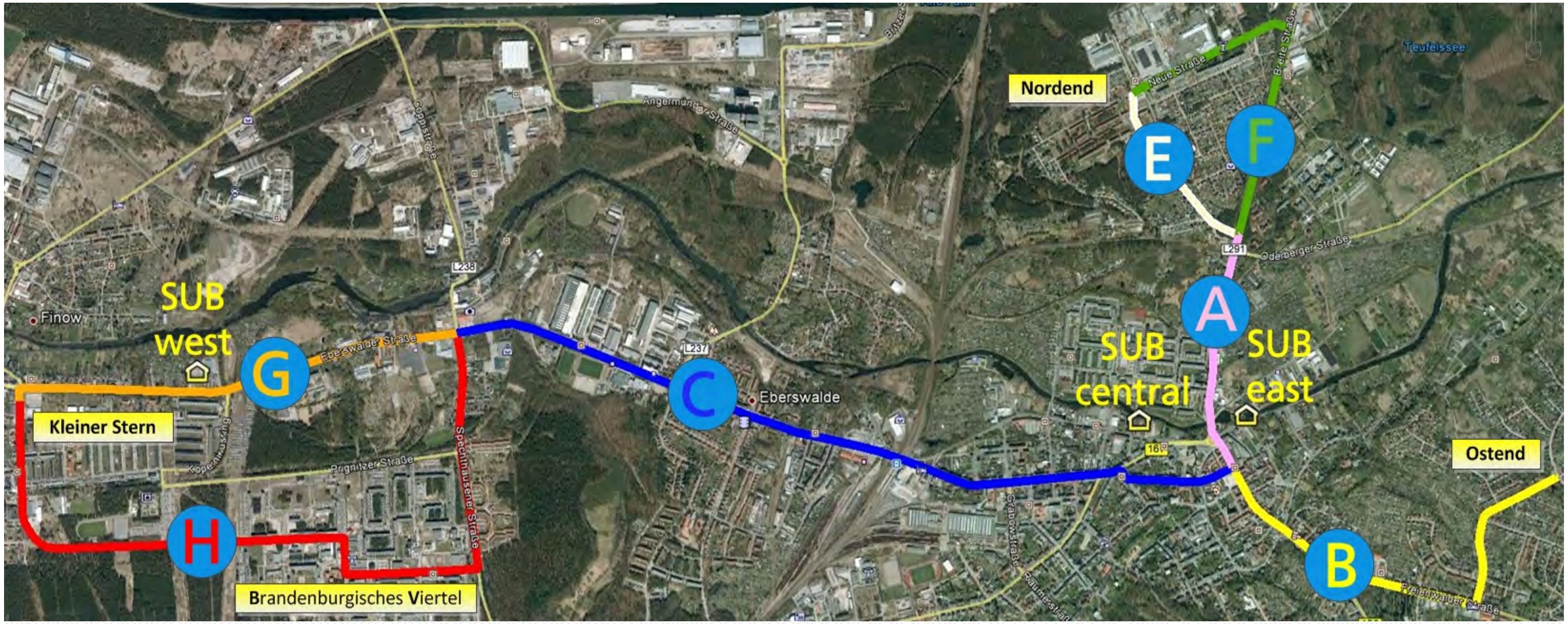
Calculation example

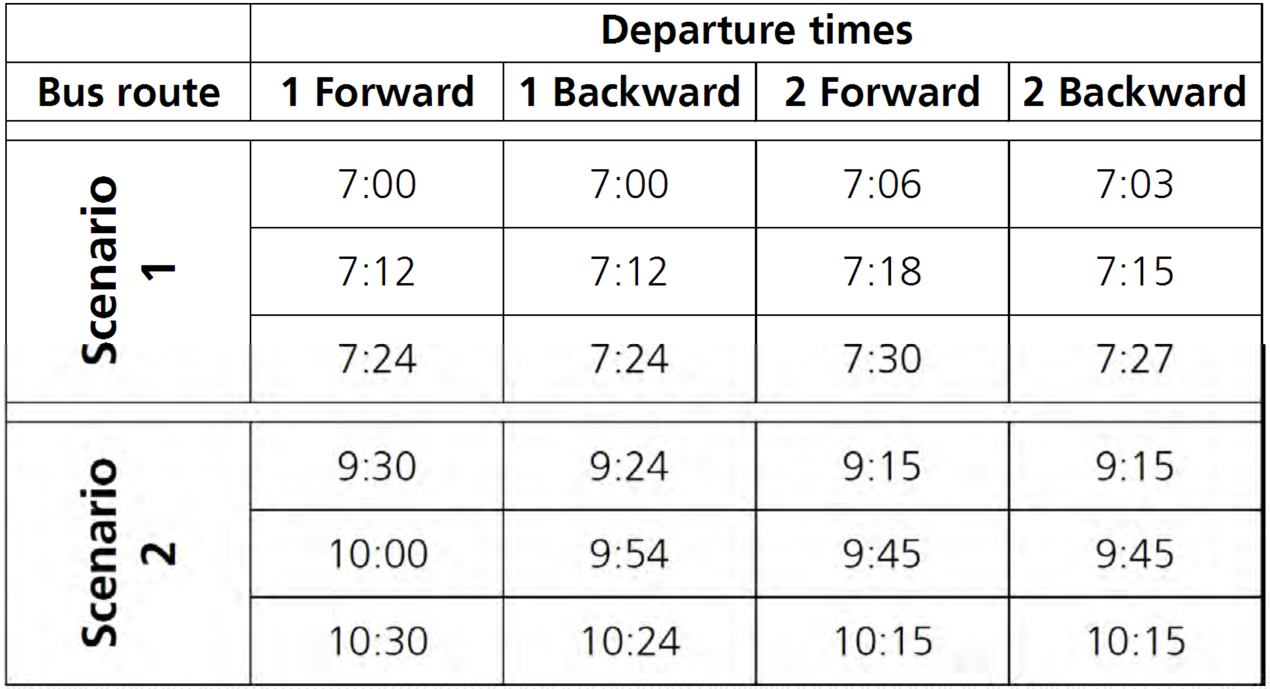
Route services



Source : Google

- 1f: Nordend → Kleiner Stern 1b: Kleiner Stern → BV → Nordend
- 2f: Ostend → BV → Kleiner Stern 2b: Kleiner Stern → Ostend

Calculation example
Schedule sections



	Departure times			
Bus route	**1 Forward**	**1 Backward**	**2 Forward**	**2 Backward**
Scenario 1	7:00	7:00	7:06	7:03
	7:12	7:12	7:18	7:15
	7:24	7:24	7:30	7:27
Scenario 2	9:30	9:24	9:15	9:15
	10:00	9:54	9:45	9:45
	10:30	10:24	10:15	10:15

- Scenario 1: »work traffic« Scenario 2: »holiday traffic«
- Annual mean: 65% »Scenario 1« / 35% »Scenario 2«

Calculation example
Vehicles

AB3

Vehicle data	Unit	Solaris	Comments
Net weight	t	19,9	
Transport capacity	pers.	143	
Mean load condition	-	1/4	assumption
Rated power	kW	250	
Maximum starting acceleration	m/s²	1,3	
Maximum braking decceleration	m/s²	- 0,8	
Driving wheel diameter	m	0,945	
Gear ratio	-	6,2	
Rolling friction coefficient of the tires	-	0,007	assumption
Power of auxiliaries (continuous)	kW	21/30	SO/WI* (assumption)
Voltage level of braking resistor	V	720	
Minimum electrical voltage of vehicle	V	480	
Energy storage system data		**LS Mtron**	
Cell type		LS3000	
Maximal voltage	V	790	assumption
Minimal voltage	V	519	assumption
Nominal capacity	F	10,156	
Usable energy content	Wh	500	
Internal resistance (DC)	mΩ	144	cells only

* SO – summer operation WI – winter operation

Source : BBG Eberswalde

- Prior use of braking energy for heating/air conditioning
- Annual mean : 42 weeks »summer« / 10 weeks »winter«

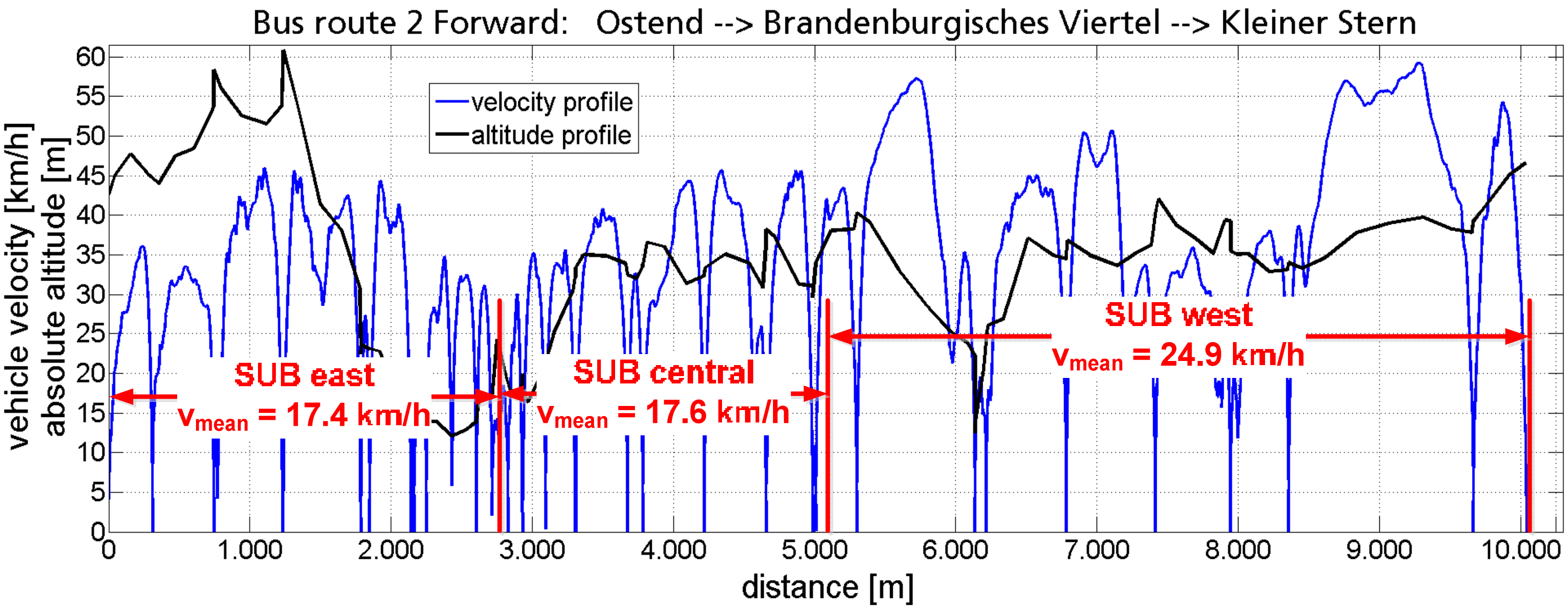
Folie 27

AB3 Das Foto hat eine sehr schlechte Auflösung. Haben Sie noch ein besseres?

Adler, Bettina; 10.10.2012

Calculation example

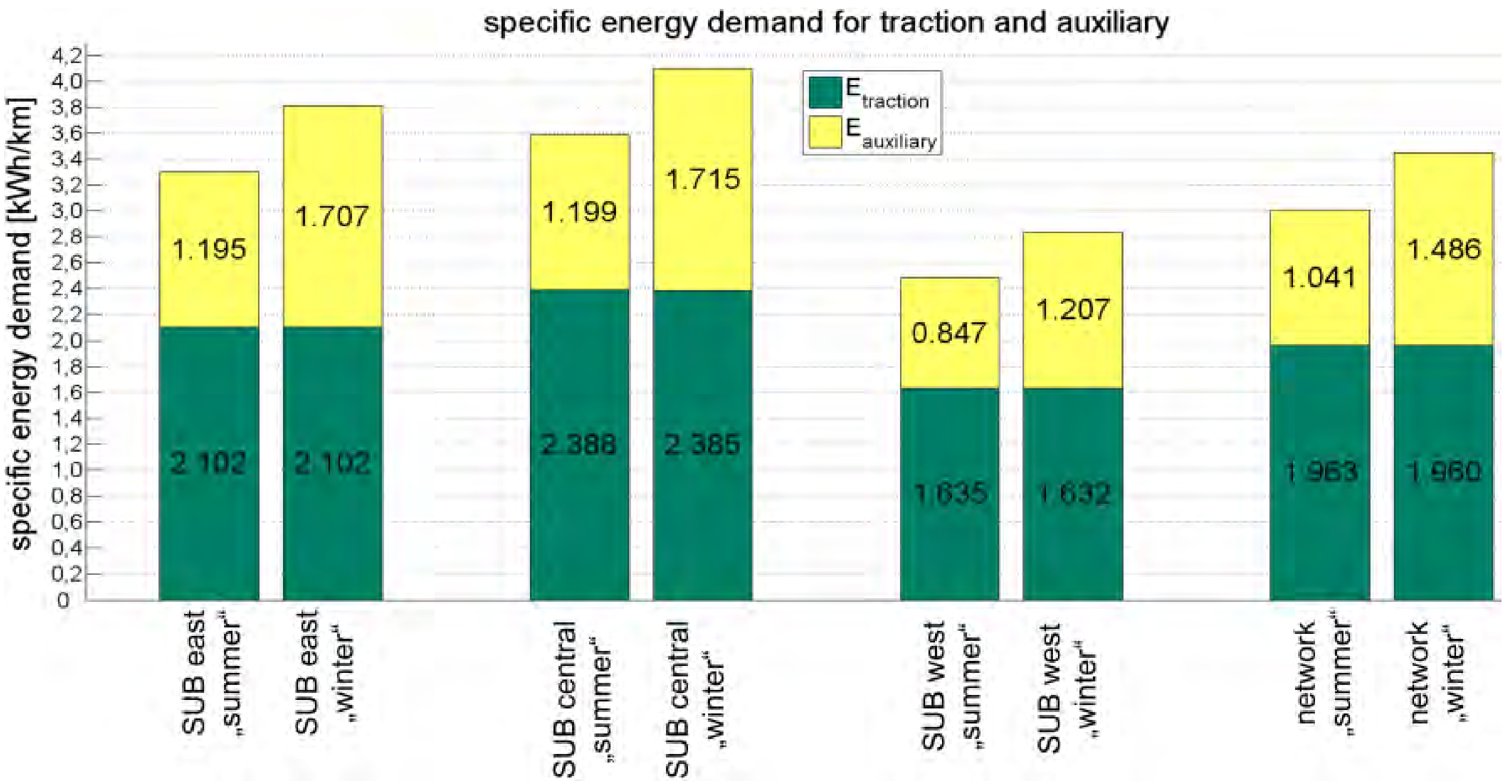
Operational profiles



- Measurement of operational profiles over a period of 6 weeks
- Derivation of the 4 required profiles by data processing

Calculation example

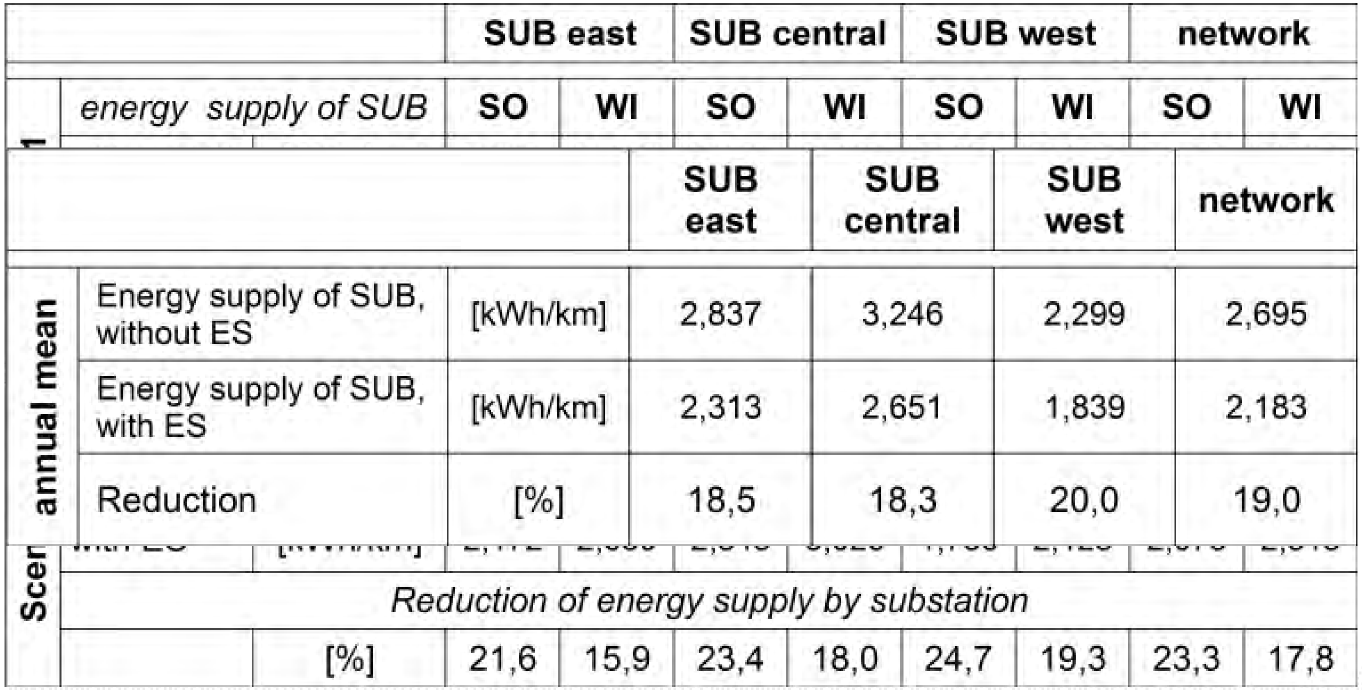
Specific energy demand



- Significant influence of velocity within the area of substation west

Calculation example

Energy-saving potential by SCAP



			SUB east		SUB central		SUB west		network	
Scen… 1	*energy supply of SUB*		SO	WI	SO	WI	SO	WI	SO	WI
	Reduction of energy supply by substation									
		[%]	21,6	15,9	23,4	18,0	24,7	19,3	23,3	17,8

			SUB east	**SUB central**	**SUB west**	**network**
annual mean	Energy supply of SUB, without ES	[kWh/km]	2,837	3,246	2,299	2,695
	Energy supply of SUB, with ES	[kWh/km]	2,313	2,651	1,839	2,183
	Reduction	[%]	18,5	18,3	20,0	19,0

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Summary

AB4

- For determination of the potential of so far unused braking energy the **measurement and data processing** is a moderate method.
- For economic utilization of available braking energy for decreasing the energy demand, a custom-designed **dimensioning of energy storage component and power electronics** is required.
- An appropriate base for the decision process for the track and fleet specific purchase of energy storage systems can be worked out by a **network simulation of the energy storage operation (mobile/stationary)**.

Folie 32

AB4	Hier würde ich die Stichpunkte enorm kürzen. Nur das wichtigste, den Rest kann man ja erzählen. Sonst ist Ihr Publikum nur mit Lesen beschäftigt und hört Ihnen nicht mehr zu. :) Adler, Bettina; 10.10.2012

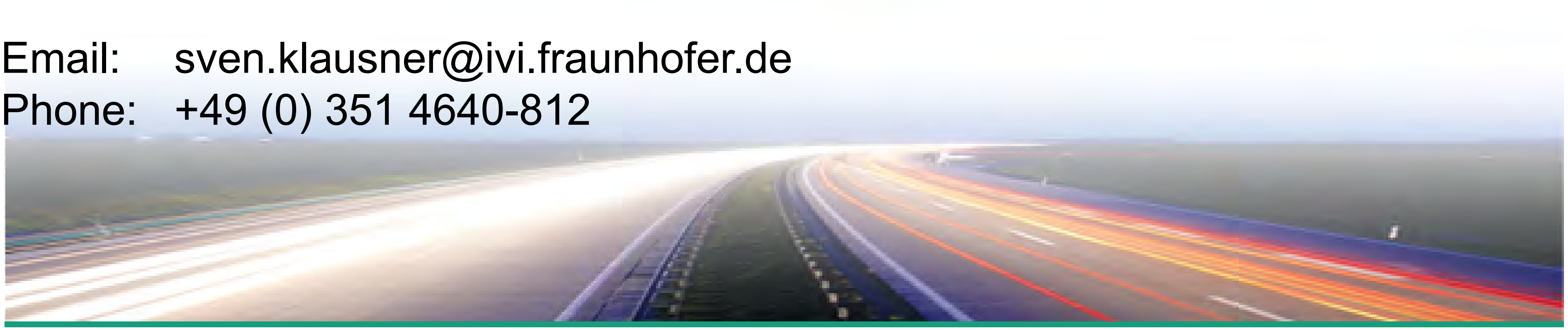
QUESTIONS AND COMMENTS

DRESDEN

Energy-saving potential of energy storage systems in public transport networks

Sven Klausner

Email: sven.klausner@ivi.fraunhofer.de
Phone: +49 (0) 351 4640-812



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Project SEB

Schnellladesysteme für **E**lektro**B**usse im ÖPNV

GEFÖRDERT VOM
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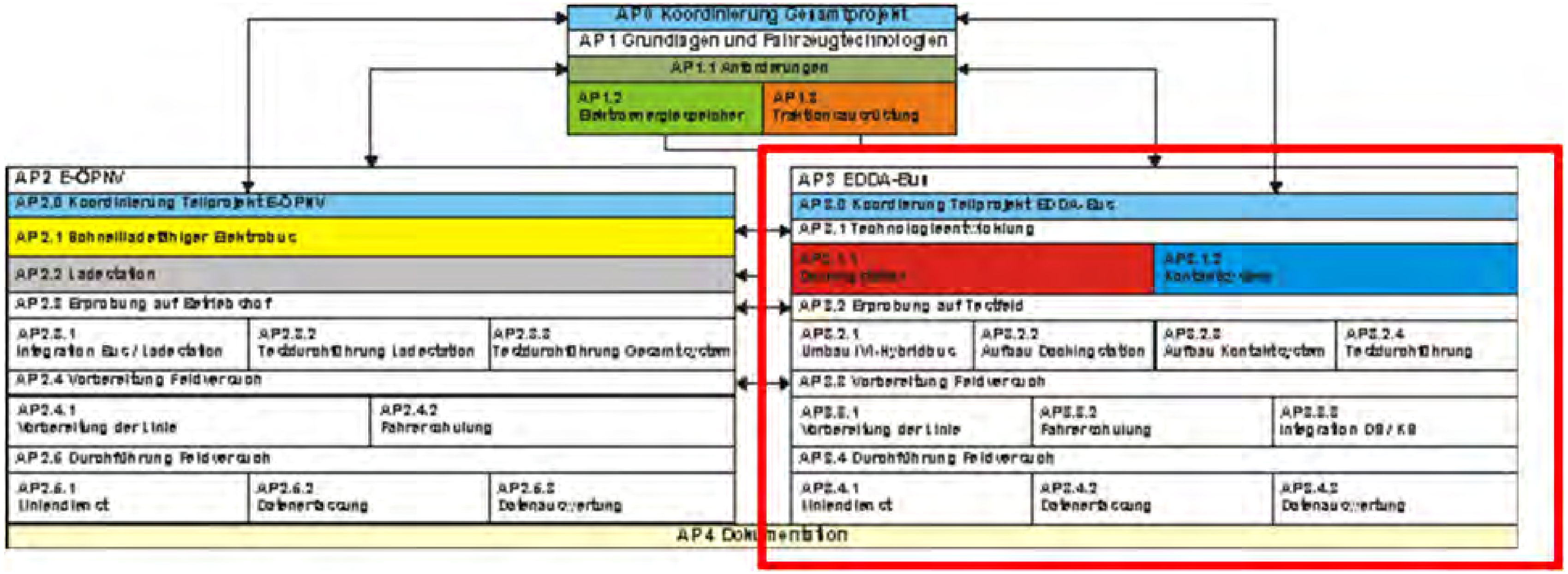
AP0 Koordinierung Gesamtprojekt
AP1 Grundlagen und Fahrzeugtechnologien
AP1.1 Anforderungen
AP1.2 Bordenergiespeicher
AP1.3 Traktionsausrüstung
AP2 E-ÖPNV
AP2.0 Koordinierung Teilprojekt E-ÖPNV
AP2.1 Schnellladefähiger Elektrobus
AP2.2 Ladestation
AP2.3 Erprobung auf Betriebshof
AP2.3.1 Integration Bus / Ladestation
AP2.3.2 Testdurchführung Ladestation
AP2.3.3 Testdurchführung Gesamtsystem
AP2.4 Vorbereitung Feldversuch
AP2.4.1 Vorbereitung der Linie
AP2.4.2 Fahrerschulung
AP2.5 Durchführung Feldversuch
AP2.5.1 Liniendienst
AP2.5.2 Datenerfassung
AP2.5.3 Datenauswertung
AP3 EDDA-Bus
AP3.0 Koordinierung Teilprojekt EDDA-Bus
AP3.1 Technologieentwicklung
AP3.1.1 Dockingstation
AP3.1.2 Kontaktsystem
AP3.2 Erprobung auf Testfeld
AP3.2.1 Umbau IVI-Hybridbus
AP3.2.2 Aufbau Dockingstation
AP3.2.3 Aufbau Kontaktsystem
AP3.2.4 Testdurchführung
AP3.3 Vorbereitung Feldversuch
AP3.3.1 Vorbereitung der Linie
AP3.3.2 Fahrerschulung
AP3.3.3 Integration DB / KB
AP3.4 Durchführung Feldversuch
AP3.4.1 Liniendienst
AP3.4.2 Datenerfassung
AP3.4.3 Datenauswertung
AP4 Dokumentation

- Project executing organization VDI/VDE
- Two particular projects with (partial) identical project partners
- Coordination by Fraunhofer IVI (Dr. Thoralf Knote)

Particular project EDDA

Fraunhofer IVI

vossloh KIEPE

HOPPECKE POWER FROM INNOVATION

M&P

schunk

DVB DRESDNER VERKEHRSBETRIEBE AG

- Duration: 02/2012 – 01/2015
- Project budget IVI: 3 employees, 200 T€ for material
- Further partners: Göppel Bus, TÜV Rheinland

Folie 35

AB5 Wofür steht particular? Ich würde nur "Project EDDA" schreiben.

Adler, Bettina; 10.10.2012

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Sunday, July 31, 2011

Suppliers eye market for ‘hybrid’ streetcars

Written by Douglas John Bowen, Managing Editor

1

In the near future, portions of North American streetcar routes likely will receive their power supply from a source underneath the vehicle floor, mixing such supply with more traditional overhead wire. Ansaldo STS’ TramWave conditioned contact line, shown here, is designed to supply power in mixed-traffic locations, with segments energized only when a streetcar passes overhead.

Washington, D.C. and Cincinnati may become the first U.S. cities to purchase dual-power streetcars—and they’ll have plenty of options to choose from.

Just as U.S. streetcar development gains momentum, and U.S. LRT expansion continues apace, objections to “ugly wires” have gained respectable standing. Those objecting now include not just anti-rail partisans or Not-In-My-Back-Yard protesters, but those concerned with visual aesthetics, and/or historical context, of a given location.

Despite published statements suggesting overhead wire power supply is more expensive, dangerous, and always visually offensive, it’s highly unlikely that the traditional power source will disappear, or even be discontinued, as an option. Various claims of lower maintenance costs (often made by advocates and not the suppliers themselves) also are suspect; overhead wires do need repair and replacement, but snow, ice, wind, or even dirt and dust can also disrupt any in-ground power alternative.

"Off-wire technologies are an addition, not a replacement, for streetcars," one supplier representative remarked at the American Public Transportation Association Rail Conference in Boston in June. "It's like a hybrid automobile; think hybrid streetcar, mixing its power sources to best result."

Such results could be critical as continued development of LRT and streetcar systems, arguably the fastest-growing passenger rail segment in the U.S., moves ahead. Responding to the demands of the potential customer, numerous equipment suppliers are offering a solution, or at least a compromise: dual-power streetcars (or LRT), supplied for much of their routes by traditional overhead wire, aided by a second power source for specific (and, at the moment) somewhat limited distances.

The suppliers have at least a three-year headstart, benefitting from reacting to similar concerns voiced by European cities eager for streetcar use balanced against historic or other urban concerns.

Some hybrid streetcars operate in similar fashion to a hybrid automobile, tapping batteries or fuel cells as their second source of power. CAF, Siemens, Kawasaki, and Kinkisharyo produce products in this mold, with Clackamas, Ore.-based United Streetcar LLC promising a "United 300" model wireless option to debut soon.

A second option is to offer power not from overhead, but underneath the vehicle. Alstom, Ansaldo STS, and Bombardier each provide such alternatives based on European development which they believe are ripe for U.S. markets. Each (or all) may be right, as evidenced by Washington's District Department of Transportation's recent evaluation of six suppliers for its planned streetcar network, now under initial construction.

Ground(ed) supply

Ansaldo STS' TramWave System uses a continuous conduit duct embedded in the ground running between the rails. Power is provided by segmented, insulated conductor strips ranging between 3 and 5 meters in length with each segment activated as the train passes overhead. to be powered. A ferromagnetic belt in the conduit lets electricity flow to the streetcar when contact is made with the power collector. Gravity causes the magnetic belt to fall back into place once a train passes by, thereby cutting off the power supply. TramWave can be installed on a variety of vehicles, and can be integrated with traditional catenary lines.

Alstom Transportation's Aesthetic Power Supply (APS) System is credited by many as the first modern wireless option offered to the market. It taps power units underneath track, with 8-meter-long conduit segments separated by 3-meter insulated joints. Antennae in the APS collector unit send a coded radio signal to the power unit to activate it. Alstom's APS (originally Alimentation par Sol) also carries a third power source, a backup battery, in case of emergency. Bordeaux, France opened a streetcar operation in late 2003 using APS, provided by an Alstom-Systra joint venture to power Alstom Citadis trams.

Bombardier Transportation's Primove System also is in real-world operation, debuting as a test segment in Augsburg, Germany, in 2010. Using a conduit line beneath the ground and between the rails, Primove employs inverters connected to a power network at 750v DC. When a segment is energized, a magnetic field is created, with trains equipped with pickup coils to receive the power and convert it for propulsion. Primove conduit segments also are activated only when a train is in immediate proximity. Bombardier claims that Primove is able to operate in all climates due to its contactless nature.

Batteries (or similar) are included

If marketing drives U.S. decision-making, Kinkisharyo’s ameriTRAM may capture customers in the very near future. The company has touted its e-Brid System relentlessly in the past year with a U.S. tour of its prototype streetcar, with several cities, including (but not limited to) Cincinnati, Dallas, and Washington, D.C., voicing explicit interest.

“I liked what I saw — a lot,” Cincinnati Mayor Mark Mallory said following an ameri-TRAM demonstration in his city. “It comes with some very attractive advantages.” AmeriTRAM is equipped with a lithium-ion battery with an advertised range of five miles, designed to recharge when the vehicle operates under conventional overhead wire. That range might be tested in Cincinnati, where some steep hills make for less-than-flat operational terrain.

Kawasaki Rail Car, Inc. relies on a conventional nickel metal hydride battery technology for its Smooth WIn MOver (SWIMO) streetcar. The company says the battery can recapture 20% of its capacity within five minutes at station stops. Kawasaki claims a battery range of 10 kilometers (about 6 miles). The company’s Gigacell is small enough to be installed under vehicle seating. Though it was unveiled in 2007, and featured in Kawasaki displays at U.S. rail-related conferences and exhibitions since then, the company has maintained a fairly low profile in the U.S. market, which nonetheless has begun to take notice of the option.

Siemens Sitras Hybrid Energy System (HES) is a serious contender for U.S. streetcar expansion if only because Siemens Mobility is a current powerhouse supplier of streetcar and LRT vehicles in the nation. Siemens also uses a nickel metal hydride battery, aided by a double-layer capacitor. Siemens says its product can be retrofitted into existing equipment, allowing existing U.S. systems to consider wireless expansion prospects without requiring a fleet overhaul. Siemens claims a battery range of about 8,200 feet, or about 1½ miles, before recharging is required, with recharging assisted by regenerative braking as well as at station stops.

Lisbon, Portugal’s Metro Sul de Tejo network introduced Siemens HES equipment to part of its system in November 2008.

CAF’s ACR, the Spanish acronym standing for “Rapid Charge Accumulator,” is in operation in Seville, Spain, with an onboard supercapacitor designed to charge and discharge energy quickly; it also benefits for regenerative braking and recharging at station stops. CAF claims station stop recharges can take place in as little as 20 seconds.

‘Wireless zone’ drives D.C. shopping

Ask Scott Kubly if the District of Columbia used stealth to advance its proposed 37-mile streetcar system for the nation’s capital, and he suggests any low visibility was prompted by caution, not cunning. “We needed to build a comfort zone” before moving ahead with any project, he says. “We didn’t know what we didn’t know.”

The lack of knowledge included the extent of limits on overhead trolley wire for the federal districtwithin Washington, and whether such limits would gut any citywide streetcar system. Critics and even streetcar advocates nationwide for years said such a limitation would squelch any meaningful return of streetcars within city limits. “In essence it’s Not-In-My-Back-Yard, codified into law,” one advocate observes.

But Kubly, until last month the DDOT associate director working with pro-rail forces and coaxing various opponents, sought wireless streetcar capability earlier than many to bridge the “no-wire” zone and overcome reluctance, notably from those concerned with visual obstruction of historic view corridors.

Given the relative wealth of wireless streetcar products now making their debut, DDOT likely will be among the first to shop the market. DDOT is developing specifications which will incorporate “one-mile of no-wire operations,” augmented by more traditional trolley wire propulsion outside the no-wires zone, in its long-range plans.

Among the companies DDOT has evaluated as part of its search: Bombardier Transportation, Inekon Group, Kawasaki Rail Car, Inc., Kinkisharyo, Siemens Mobility, and U.S.-based newcomer United Streetcar LLC.

More immediately, DDOT continues construction on its first two streetcar segments, along H Street and Benning Road in the Northeast, with access to Union Station, and in Anacostia, within the district’s Southeast quadrant.

Though targeted completion dates now have slipped one year to 2013, the city’s first two streetcar segments have advanced faster and farther than comparable projects in the district’s suburbs, notably the Columbia Pike streetcar plan for Arlington and Fairfax counties in Virginia (and possibly including Alexandria, Va.). “The suburban parts of the region are catching on to this,” Kubly says. But he hopes D.C. will get there first— in part with wireless streetcar capability in place to augment more traditional overhead power.

If DDOT succeeds, streetcars, last seen in operation within the district in January 1962, will return after an absence of more than 50 years.

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Light Rail Without Wires - A Dream Come True??

JOHN D. SWANSON
PARSONS BRINCKERHOFF QUADE & DOUGLAS, INC.
(PB Transit & Rail Systems, Inc.)

ABSTRACT

Since the dawn of electrification over a century ago, overhead wires have been used to convey electrical power and communications to offices, factories, and homes. Transportation too, in the form of streetcars and more recently, light rail vehicles, has also commonly used overhead wires to transfer power to vehicles. Many people consider these wires to be unsightly and undesirable, but reluctantly accept them as a necessary evil because of a lack of practical alternatives. Only a few cities have managed to run significant streetcar systems without overhead wires for any length of time and all such systems are now defunct. In recent years, new technological developments in hybrid vehicles and ground level switched contact systems are at last showing signs of offering some practical alternative solutions. For light rail applications, the most promising development is the INNORAIL ground level switched contact system now being applied to the new light rail system in Bordeaux, France which will be examined in detail. Based on the significant progress being made there, it seems likely the dream of having a practical alternative to overhead wires will be coming true in the very near future.

WHY DO WE HAVE OVERHEAD WIRES?

Dislike of overhead wires in the urban environment is not a new phenomenon. From the introduction of electrically powered apparatus over a century ago, people have protested against the erection of overhead wires, especially in the more affluent sectors of the city. As far back as the 1890's, major established, affluent cities such New York City, Washington, D.C., London, and Paris garnered enough political support to enact city ordinances prohibiting the erection of any type of overhead wires in specifically designated areas. For most cities, however, financial and practical considerations usually ended up winning the argument and as a result, overhead wires were erected.

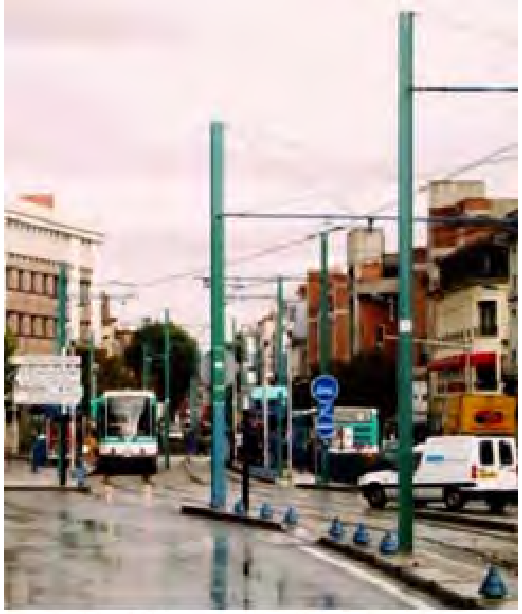
During the development of the fledgling streetcars, a wild flurry of new and often impractical electric power supply approaches were tried, from the first experimental battery powered passenger carrying cars of 1847, to the first successful electric streetcar system, built by Frank J. Sprague in 1888 for Richmond, Virginia. Sprague's system, which was the first to use both an overhead contact wire and trolley poles, demonstrated such a clear superiority over other approaches of the time that it soon became the industry standard for supplying power.

Later developments have mostly focused on refining this relatively simple, economical and reliable direct electrical contact technology, known today as the overhead contact system or OCS. These systems have operated efficiently and mostly unchallenged until today, with the biggest design change being a gradual transition from using trolley poles on the streetcars to pantographs on the more modern version, the light rail vehicle. As a result, almost every streetcar / light rail system in operation or being planned today uses an overhead wire to supply power.

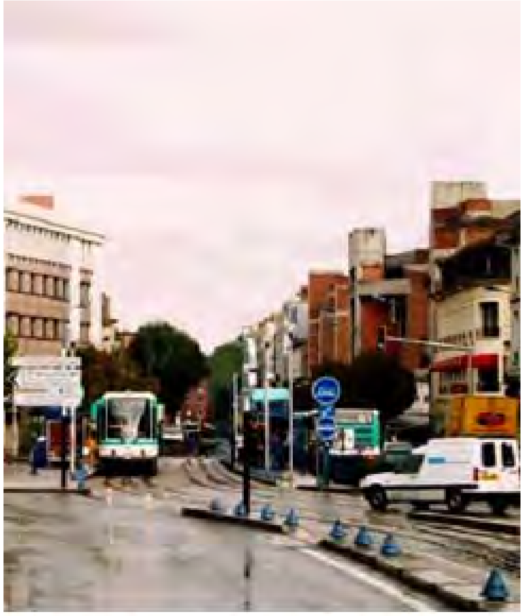
A CHANGING URBAN LANDSCAPE

In recent years, with cost effective improvements in cable insulation and burial techniques, there has been a renewed interest in improving the quality of the urban cityscape. New housing additions have sought to create attractive neighborhoods by burying all cables and concealing transformers. Cities have undertaken expensive area improvement programs to eliminate garish billboards and signs, and to place local power feeders and communications cables underground, greatly improving the appearance of the area and generating public pride.

As those of you who have undertaken the task of trying to add a new light rail system to an established neighborhood will know well, the concept of erecting overhead wires for a new system is unpopular with the public. Just so we do not forget, this is what happens to the urban landscape when overhead contact wire is erected.



With OCS Wires



Without OCS Wires

Even with attempts to minimize the visual intrusion of the OCS system, the impact is still significant. However, the elimination of these wires and their supporting structures is a problem for light rail systems because up to now, there has been no practical alternative to OCS. Let us examine some ways in which we might resolve this problem.

ALTERNATIVE SOLUTIONS

There are a number of potential alternatives available, but most either pose extreme technological challenges or are fatally flawed in some basic characteristic. Over the years, through the process of development and elimination, three potential solutions stand out as being the most promising, namely:

- Conduit power (old, but proven technology)
- Hybrid vehicles (combination of power sources including fuel cells, super capacitors, flywheels, microturbines, batteries and internal combustion engines)
- Ground level switched contact systems (center running 'third rail')

To address these adequately would be beyond the scope of a single paper, although an attempt has been made to provide an overview in a earlier paper entitled *At Last, Light Rail Systems Without Overhead Wires* published in the proceedings of the APTA 2003 Rail Transit Conference. Since the publication of that paper, it has become clear that resurrection of the old conduit system remains impractical from both a cost and operational standpoint, while the hybrid vehicle development program appears to be stalled indefinitely. Therefore we will concentrate on the ground level switched contact systems and in particular on the INNORAIL system currently being commissioned in Bordeaux, France.

GROUND LEVEL SWITCHED CONTACT SYSTEMS

Based on proven third rail power transfer systems, a promising approach could be to place the power supply rails directly between the running rails and pick up the power using third rail type shoegear. The basic concept will remind many of Lionel and Marklin model trains. The problem with this approach is of course the danger inherent in having ground level power rails energized at 750 Vdc when the rails are accessible to the public. This problem can be solved by making the power rails a series of separate sections - the system can the switch each the section on or off individually so that a power rail section is energized only when the vehicle is directly over it.

There have been a number of recent attempts at making this approach work. These include the E-Tran bus system developed for Minnesota by Nick Musachio, (1986 - 1992), the STREAM bus system for Trieste, Italy developed by AnsaldoBreda, (1994 to present), the ALISS LRV system for Bordeaux, France developed by Alstom, (1999 – 2002) and the INNORAIL LRV power system developed by Spie Rail, a subsidiary of Spie Entertrans (1999 to present), also for Bordeaux, France. Only the ALISS and the INNORAIL systems were specifically designed with sufficient power capacity for application to a light rail system.

Out of all these, the INNORAIL system is currently the most advanced and well on its way to a significant LRV system application in Bordeaux.

THE BORDEAUX LRT SYSTEM AS A DRIVER FOR NEW TECHNOLOGY

When the new Bordeaux LRT system vehicle specification was released for tender to potential suppliers in 1999, it included a requirement to provide a power supply system that did not use overhead contact wires through an architecturally important and aesthetically sensitive section of the city adjacent to the Cathedral, some 1.8 miles [3 km] of the system route. Historically, it is important to note that even in their earlier streetcar days, Bordeaux never had overhead contact wire in the town center, as a conduit power system provided vehicle power until the system was dismantled.

Potential suppliers experimented with various options to meet these requirements, including flywheel energy storage. Upon close evaluation, all existing technological solutions had significant drawbacks, including weight, cost, space requirements and performance between stations when stopping was required.

Eventually, it was determined that a completely new development, the ground level switched contact system, known in France as the APS system, short for **A**limentation **p**ar **S**ol, was required to provide the reliable system needed. Two competing versions of this system were subsequently developed and evaluated, the Alstom ALISS system and the Spie Rail INNORAIL system. In the summer of 2002, the INNORAIL system emerged as the final choice for implementation in Bordeaux.

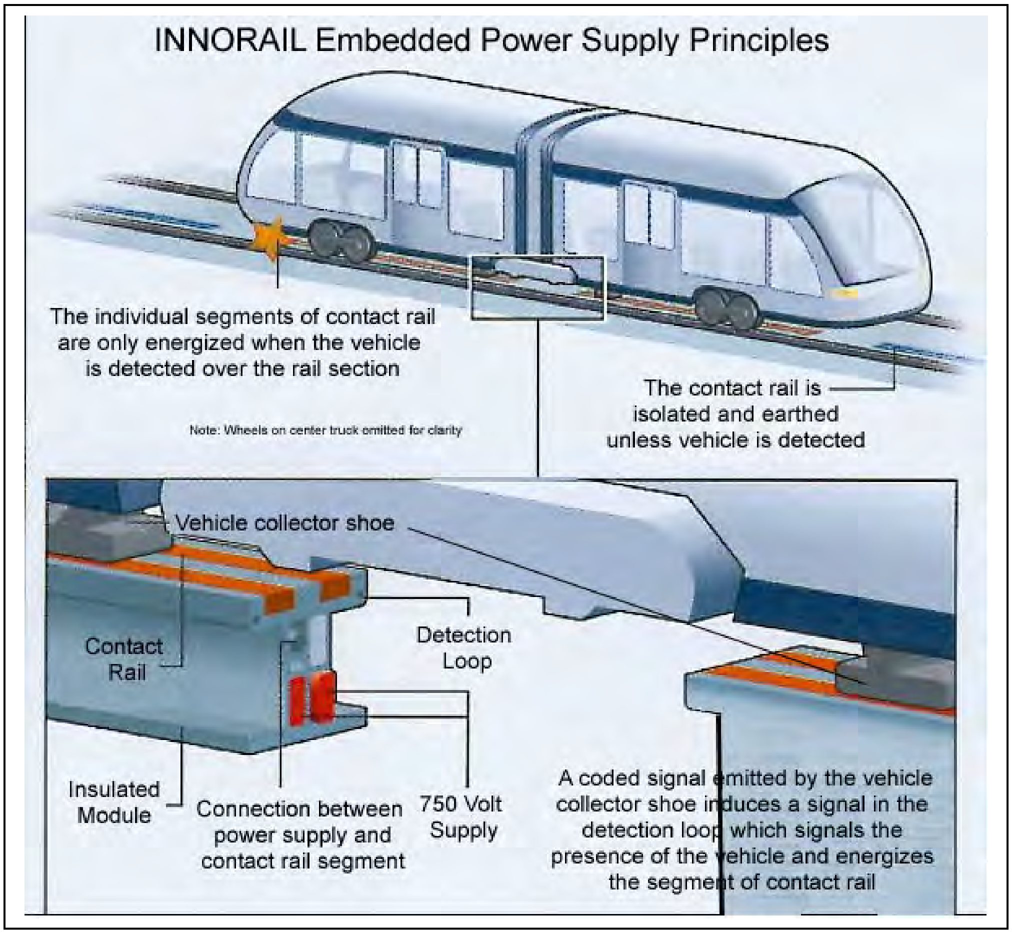
More importantly, the requirement for INNORAIL equipped sections of the Bordeaux system was now to be increased to 6.3 miles [10.5 kilometers], nearly half the total 15.5 mile [25 kilometer] Phase 1 system length. This is more than twice the initial requirement, clearly a vote of confidence by the City of Bordeaux in the viability of the technology.

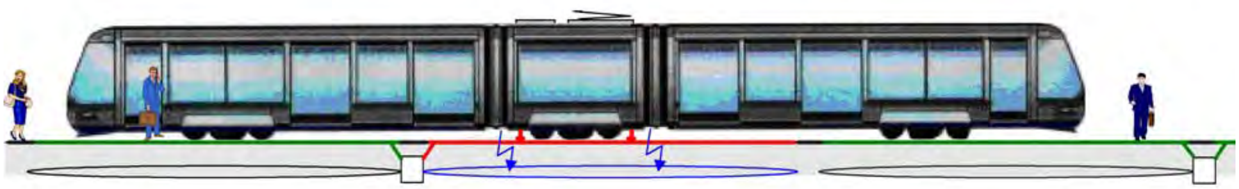
An important lesson to learn from this is that strong and unwavering political support for a new technological development required to meet a perceived public need, will produce the motivation needed to develop and adopt it.

INNORAIL BASICS

As is common with all the earlier ground level contact system approaches, the INNORAIL system uses a series of switched contact rails installed between the running rails, separated by insulated rail sections to ensure complete electrical isolation of each section. Each individual section is only energized when its local power rail contactor receives and verifies a low power, specially coded signal coming from the vehicle transponder that can only be detected when the vehicle is directly over the section. At all other times, the power rail segment is automatically grounded.

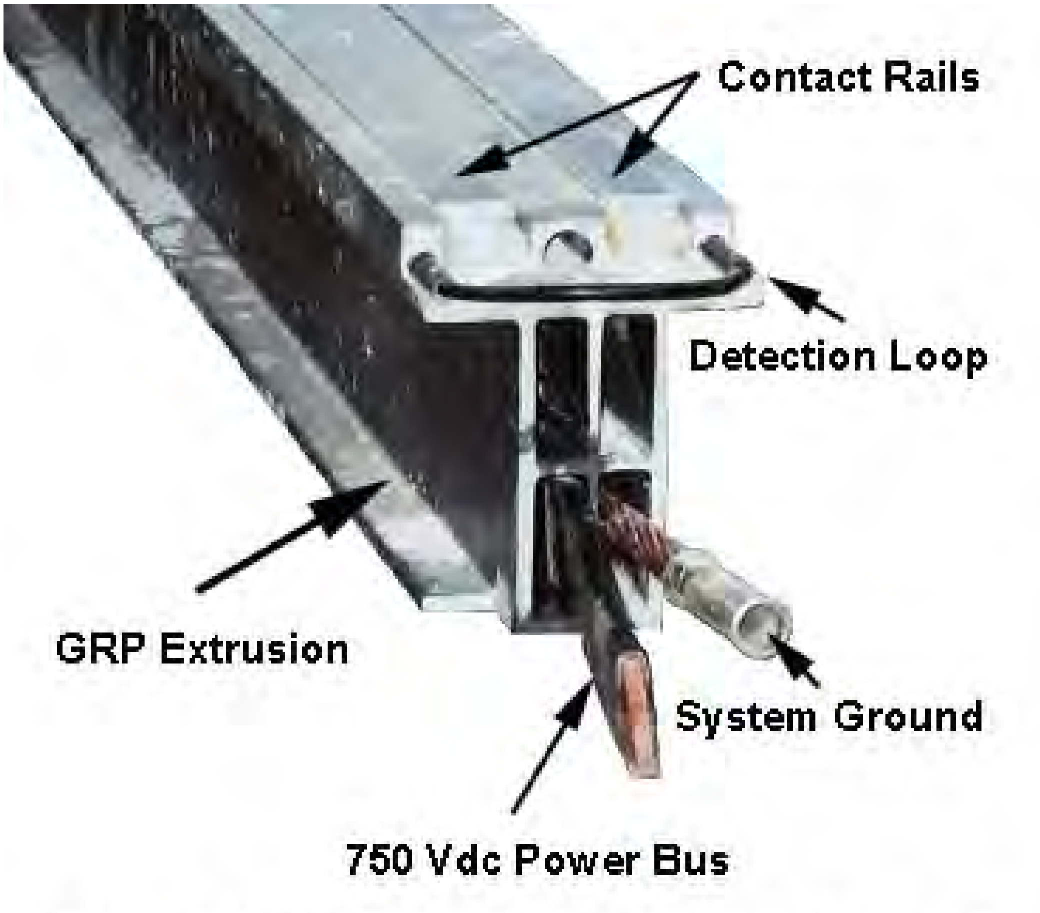
Two sets of pickup shoes are provided on the vehicle to provide continuity of power as the vehicle crosses insulated sections. The basic elements of the system are illustrated in the following two diagrams.


INNORAIL Embedded Power Supply Principles
The individual segments of contact rail are only energized when the vehicle is detected over the rail section
Note: Wheels on center truck omitted for clarity
The contact rail is isolated and earthed unless vehicle is detected
Vehicle collector shoe
Contact Rail
Detection Loop
Insulated Module
Connection between power supply and contact rail segment
750 Volt Supply
A coded signal emitted by the vehicle collector shoe induces a signal in the detection loop which signals the presence of the vehicle and energizes the segment of contact rail



INNORAIL Ground Level Switched Contact System

The INNORAIL power rail sections are designed with a very low profile, standing only 6.7 inches [17 cm] high. This allows them to be easily accommodated in virtually every type of track installation, including ballasted track. The INNORAIL system may also be retrofitted to many existing LRT systems.



INNORAIL Power Rail Cross Section

Ballasted Track

Paved Track

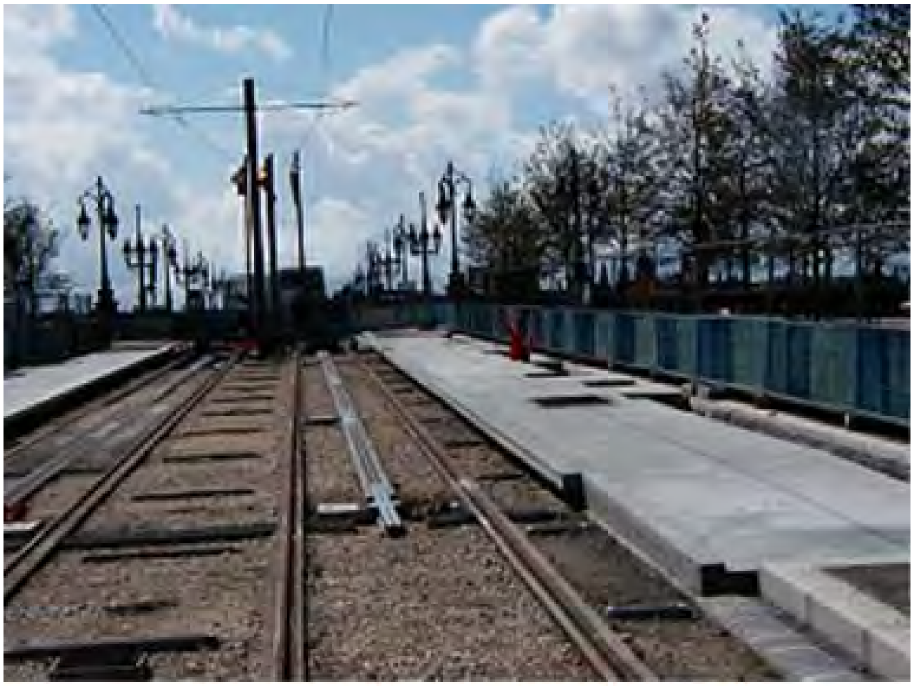
Embedded Track

Grass Track

Electrically dead zones caused by an occasional faulty power rail segment contactor are traversed using vehicle on-board emergency battery sets with automatic transition to battery power when needed.

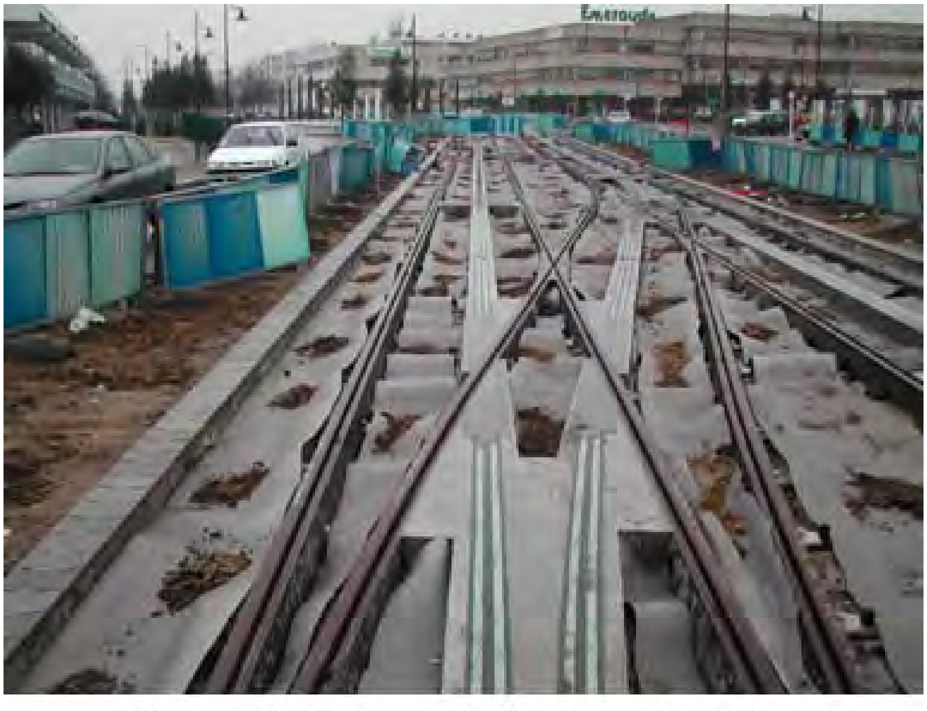
All active elements of the system are fully modularized, easily accessible and quickly changed out in case of a fault.

In Bordeaux, transitions from INNORAIL to conventional OCS (and vice versa) are manually initiated by the vehicle Operator with the vehicle stopped at a passenger platform. This transition is completed within normal station dwell times. According to the manufacturer, it is also possible for this process to be automated allowing the transition to be accomplished with the vehicle moving.



Station Transition Point

The crossing of special track work such as turnouts and crossovers is made using special insulated sections, which allow the pick-up shoes to cross the running rails.



Crossing Special Trackwork

INNORAIL SYSTEM DEVELOPMENT

Development of INNORAIL began in the Spie Rail works in Vitrolles in the south of France in early 1999. Full size system component mockups were installed on streetcar Line 68 in nearby Marseille by December of 1999, with fully functional prototype components installed by May of 2001. This allowed the operation of a limited proof of concept installation using a modified 600 Vdc high floor vehicle and 1968.5 feet [600 meters] of sectional power rails, of which 492 feet [150 meters] were in installed in city streets.

Proof of Concept

Meanwhile, in the north at Ollainville, track components in a variety of installation configurations were being subjected to a simulated 30 years of street traffic by the RATP Test Laboratories, being repeatedly crossed by 11 ton rubber tired vehicle loads.

Endurance Testing

By 2002, INNORAIL early production components had been installed on 2296.6 feet [700 meters] of LRV test track at the Alstom La Rochelle factory where the new Citadis LRVs for Bordeaux are being constructed. Extensive testing followed, using a state-of-the-art 100% low floor Citadis vehicle operating at 750 Vdc. To date, over 2100 miles [3500 kilometers] of endurance running tests have been performed, including crossing special trackwork and automatic transition to emergency battery power.

System Testing

THE BORDEAUX LRT SYSTEM

As was noted earlier, the Phase 1 Bordeaux system length (Lines A & B) totals 15.5 miles [25 kilometers], of which 6.3 miles [10.5 kilometers] or nearly half the system is INNORAIL equipped. The INNORAIL equipped sections are located in the old city center, on the historic stone bridge crossing the Garrone River, on Line B as far as Talence, and two short sections in Lormont and Cenon. The entire Phase 1 system is scheduled to be in revenue service by the end of 2003.

Old City Center

Garonne River Bridge

Phase 2 of the development (Line C) will add another 11.6 miles [18.7 km] to the system. The percentage to be equipped with INNORAIL has yet to be finalized, but at least 3.1 miles [5 km] are expected.

The Bordeaux LRT system development produced one of the largest LRV orders in Europe, a total of 70 X 100% low floor, air conditioned vehicles. The order breakdown is as follows:

- 6 X 107.93 foot [32.9 m] long, 213 passenger Citadis 302 and 38 X 144.36 foot [44 m] long, 300 passenger Citadis 402 100% low floor vehicles in Phase 1.
- 12 X 107.93 foot [32.9 m] long Citadis 302 and 14 X 144.36 foot [44 m] long Citadis 402 100% low floor vehicles in Phase 2.

Citadis LRV

As is the norm for European LRV operations, they run only single car trains, adding more vehicles to the system as demand requires. The system typically runs trains at 4 minute intervals (2 minutes at peak).

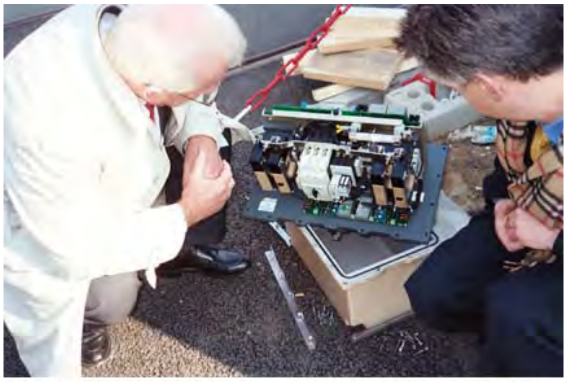
INNORAIL SYSTEM COMPONENTS

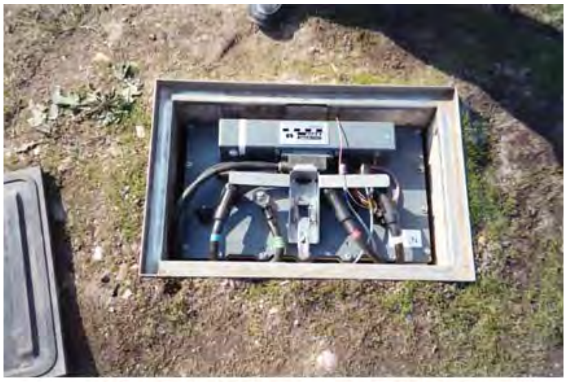
THE FIXED INSTALLATION

The fixed installation part of the INNORAIL system is made up of the following elements:

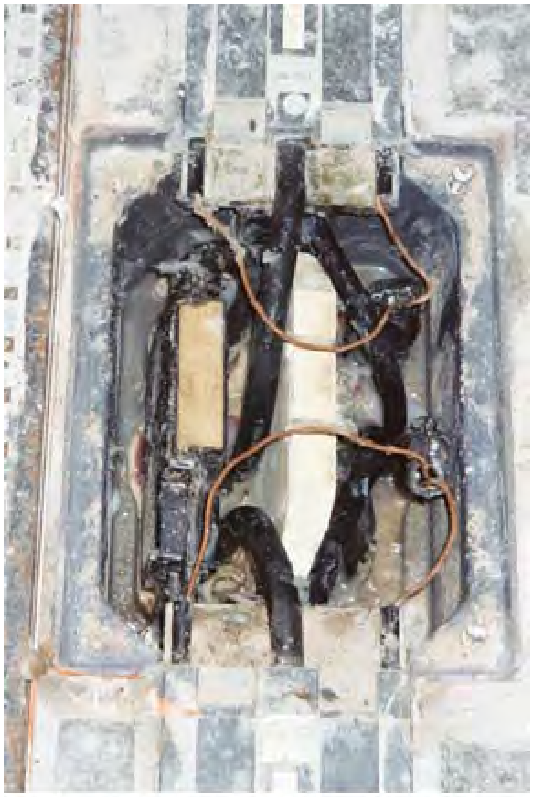
Sectional Power Rails (as mentioned earlier) – These low profile sections are typically in 36 foot [11m] lengths fitted with 26.25 feet [8 m] of conductor rail and 9.84 feet [3 m] of insulating rail. These FRP pultrusions contain integral duct banks that carry all power, ground and control cabling., as well as the vehicle detection loop for that section. These assemblies also have a spare cable duct that could potentially be leased to local fiber optic or coax cable service providers. The ratio of conducting rail to insulating rail is based on the vehicle operating speed, which in the case of Bordeaux, is 44.7 mph [20m/sec or 72 km/hr].

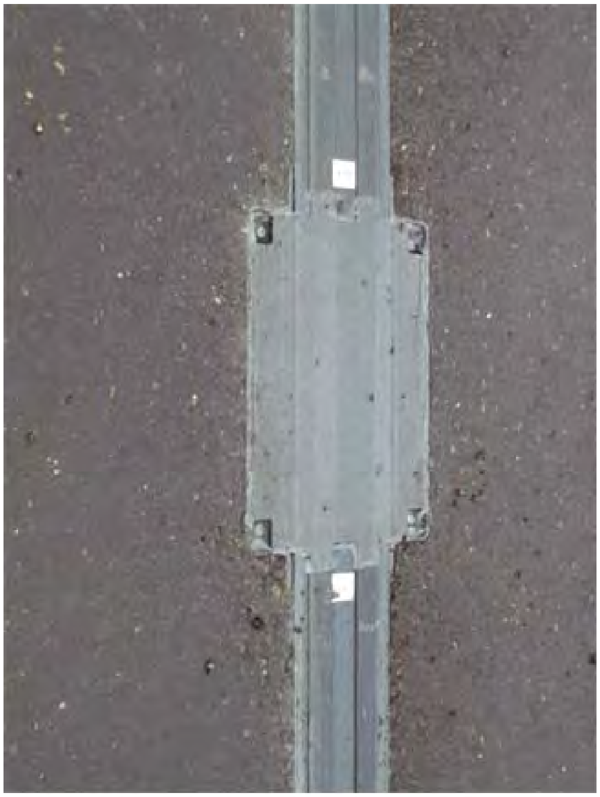
Power Rail Control Contactor Units – One is located every 72.2 feet [22 m], and controls two segments of power rail. These units are modular and can be replaced in less than 5 minutes. Although a solid state switching unit would logically be utilized, traditional contactor units were chosen for this application because the short duty cycles caused difficulties in semiconductor heat rejection at these current levels. It is still very likely that a solid state solution will eventually be applied.

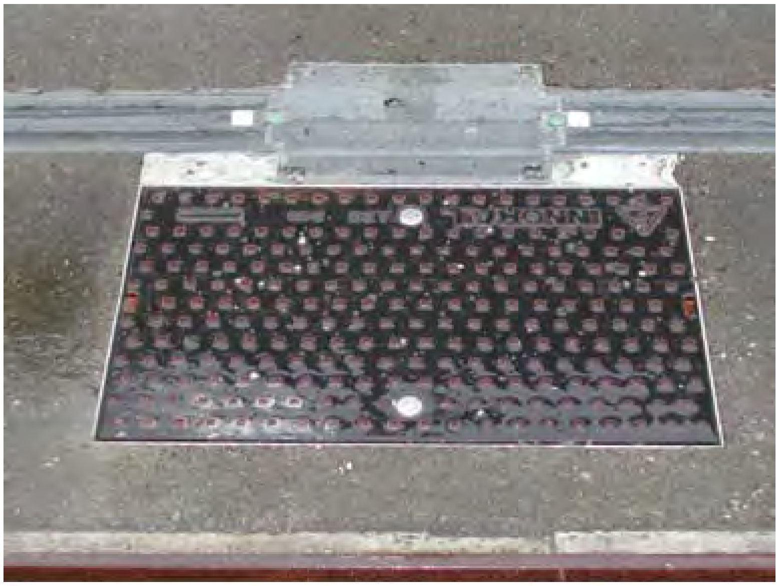

INTERIOR POWER RAIL CONTROL UNIT


INSTALLED POWER RAIL CONTROL UNIT

Insulating Junction Boxes - An insulating joint box is located every 72.2 feet [22 m] to mechanically and electrically join the ends of the power rails at all locations. These boxes are silicone sealed after all connections are made to keep out moisture.


JUNCTION BOX INTERIOR


INSTALLED JUNCTION BOX



CONTROL UNIT & JUNCTION BOX

Grounding Contactor and System Monitoring Equipment – For safety purposes, a cabinet containing a grounding contactor and system monitoring equipment is installed in each substation. The condition monitoring system is designed to detect faults in any power rail segment within 200 milliseconds, disconnect and ground the main 750 Vdc power feeder to all segments fed by that substation, automatically isolate the faulty segment and restore the system power to the remainder of the system in less than 2 seconds. These faults include, most importantly, a segment remaining live after the vehicle signal is lost and of course, short circuit or similar faults.

SYSTEM MONITORING

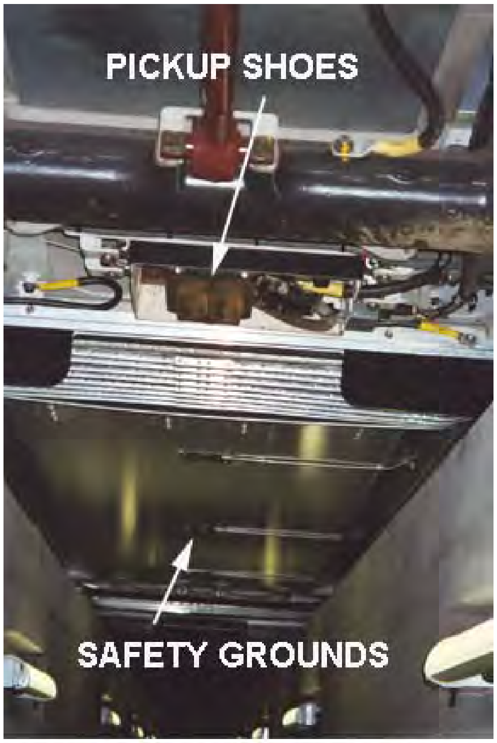
ON THE VEHICLE S

The INNORAIL system is capable of being installed on almost any type of light rail vehicle, including 100% low floor vehicles. The following additional equipment is required to operate on an INNORAIL equipped system:

Emergency Battery Set – One roof mounted unit is required on each vehicle to allow it to transition through any dead power segments. To save space, this unit is mounted under the pantograph frame on the vehicle center section. This battery set contains 63 x 12 volt sealed, aircraft certified, lead acid batteries and can provide approximately one minute of vehicle movement at reduced speed (1.8 mph [3 km/hr]). This will move the vehicle a minimum of two failed power rail segments, although 500 feet [152 m] is routinely achieved.

BATTERY BOX

Retractable Power Pickup Shoes - Two sets of center truck mounted pickup shoes are necessary for current collection, mounted at the ends of the truck. The shoegear uses graphite shoes to keep the fixed installation wear to a minimum, although in the initial stages, soft iron shoes have been used to clean and polish all the contact surfaces.



SHOEGEAR INSTALLATION

Pickup Shoe Control Box – Extra control components required to activate the pickup shoes and interlock with the pantograph controls.

Power Control Box – This roof mounted box contains the additional contactors and controls needed to for switching 750 Vdc power coming from the pickup shoes or the emergency battery set.

Cab Controls and Monitoring equipment – Additional controls required to operate and monitor the vehicle’s INNORAIL related equipment.

Safety Grounds – Extra ground points installed under the low floor section of the vehicle to suppress any possible fault conditions. These are shown in the above shoegear installation photo.

SAFETY AND CERTIFICATION

With a readily accessible ground level power system, safety is clearly a key concern. A variety of safeguards are designed into the system to prevent any single point failure from causing a hazardous condition. Independent safety certification insures that the designs perform as expected.

The safety certification process has been and continues to be addressed by various well known and respected French certification authorities and independent assessors including CERTIFER and RATP. The process so far has been as follows:

- Independent system assessment in accordance with **EN 50126** – *Railway Applications – The Specification and Demonstration of Availability, Maintainability and Safety (RAMS)* and **ENV50129** – *Safety Related Electronic Systems for Signaling* .
- Approval of the Preliminary Safety Case – this was completed in January, 2000.
- Approval of the Final System Safety Case - is currently over 90% complete and with the current progress in energizing the Bordeaux system, it is expected to be fully completed and approved by the time of this conference.

As mentioned earlier, each section of INNORAIL power rail is solidly grounded unless a signal is received by its local power control unit and separate substation monitoring circuits double check this by looking for voltage on the rail without a vehicle signal. This is to prevent any section from being inadvertently energized when not safely covered by an LRV.

Another major consideration is leakage from an energized power rail section when conditions are wet. Being on the Atlantic coast, Bordeaux is always humid and subject to frequent rain. Further, the streets are washed using salt water taken from the harbor, creating a very conductive and corrosive environment. Energized rail tests under standing salt water conditions have measured less than 5 volts leakage outside of the running rails which is considered acceptable.

Unfortunately copies of the Hazard Analysis used in the certification process and detailed design approach used to respond to these concerns are not yet readily available.

ADAPTING INNORAIL TECHNOLOGY TO US LRT SYSTEMS

A number of US-specific issues must first be addressed before the INNORAIL system can be applied to a US LRT system,. Following a technical assessment visit to Bordeaux in February of this year, the following observations were made regarding the suitability of the INNORAIL ground level contact system for US applications:

- The INNORAIL ground level contact system is well developed and has applied sound engineering principles in its design and construction. All equipment is solidly constructed and is likely to survive in its operating environment.
- The system appears to mitigate all reasonable identifiable safety hazards, thus Safety Certification in the US should be achievable. Such certification will require considerable preparation and documentation to be presented to US local certifying authorities, but can build on the experience of the Bordeaux in its safety certification process.
- Adapting to multi-car operation may be achieved by increasing the size of the main power bus with no change to the basic INNORAIL installation as the ducts can accommodate a larger cross section power bus. Substation size and spacing should remain as is normal for US typical OCS operation.
- Adapting for higher operating speeds is also said to be possible by the supplier. This would require relatively minor changes in the relative lengths of the conducting and insulating rail inserts to achieve the desired power rail switching.
- Sole sourcing is also a consideration. The INNORAIL system technology is proprietary and only available from one source, thus sole source procurement will currently be required. Fortunately, this may be allowable under section 9.h.of FTA Circular C4220.1E *Third Party Contracting Requirements.*
- Buy America requirements are also an issue in US procurements. However most, if not all, of the INNORAIL system components could be manufactured using 60% or more US manufactured components or possibly completely manufactured under license in the US.
- Adapting for higher gradient operation under section failure conditions has a higher impact as the Bordeaux LRT system profile is relatively flat. Should the US LRT system being designed have any significant gradients involving INNORAIL operation, a larger set of batteries will be required for the Emergency Battery Set, adding to the vehicle cost and weight.
- Adapting the vehicle system components to US manufactured LRVs should be fairly straightforward due to the universal nature of the additional vehicle equipment required The biggest challenges would be the fitting of the retractable shoegear in the very confined area surrounding the center trailer truck and the space / weight distribution impacts on the vehicle roof area.

- Cost is always a critical issue. Currently the system is only operating in France and has yet to be ‘Americanized, thus any cost projections are somewhat speculative. However, based on the supplier’s current estimates, the fixed installation should be within 5% of traditional OCS system costs, plus around 5% per LRV for the additional INNORAIL related vehicle mounted equipment. With series production this could become no increase in cost over OCS.
- Operation in ice and snow conditions is currently not addressed. With its fully exposed conductor rails, icing is certain to occur. There are some potential solutions, such as electrical trace heating, but they will add cost, both in initial installation and energy wise.

Adapting INNORAIL for use on US LRT systems looks possible from a cost, safety and engineering point of view as long as snow and ice are not a major factor. The author is aware of several US cities that are actively considering this technology and the number is likely to grow as the system becomes fully operational at the end of this year.

The biggest single hurdle today is availability of the system. In March of this year, the Spie Rail INNORAIL technology was sold to Alstom who are currently showing no interest in the US market for this very promising technology. It is hoped that if sufficient interest is shown here, we too may have the capability to operate without wires.

CONCLUSIONS

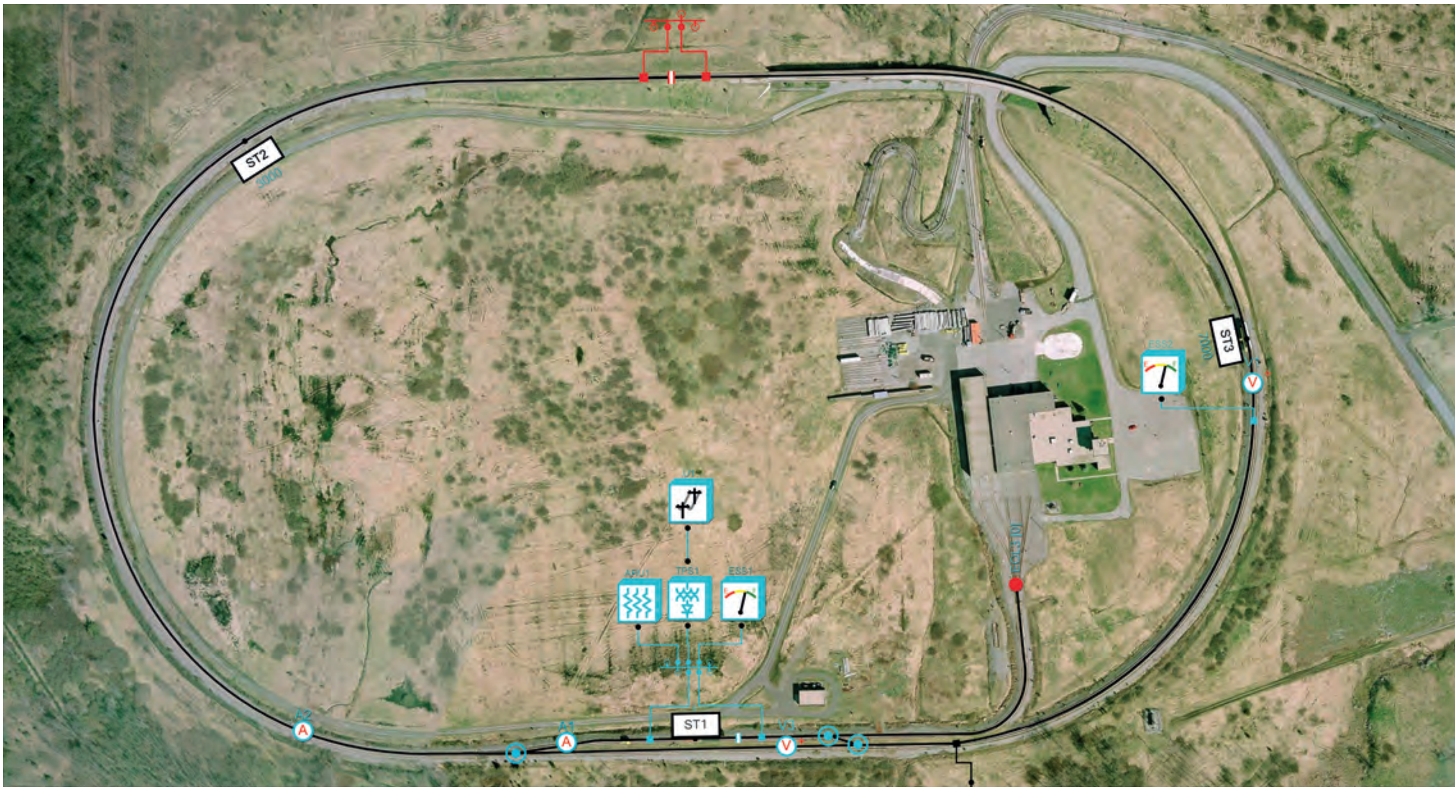
For the first time in many decades, the dream of having quiet, non-polluting, electric light rail vehicles running without any overhead wires is on the verge of becoming a reality.

The INNORAIL ground level switched contact system in Bordeaux is about to become a significant operational system, although more day to day operational experience is needed to fully prove system reliability over time. Nonetheless, this system is sufficiently developed enough that the author believes this to be a viable system and worthy of consideration for many new light rail systems.

One thing is certain, public opinion is very supportive of ‘wireless’ systems and as this technology becomes more mature and available, widespread adoption is inevitable.

EnerGplan Simulation Tool

EnerGplan screen shot



When planning a transportation system, customers are challenged to select the appropriate technology and mode of operation that will provide peak performance, lowest operating costs and the smallest environmental footprint while minimizing energy consumption.

The Solution

The *BOMBARDIER* EnerGplan** is Bombardier's newest tool to help optimize the design of power distribution systems and reduce energy consumption during operations.

EnerGplan Simulation Tool

EnerGplan is a graphical-based simulation tool that provides the transit system designer with the ability to analyze and optimize the power system configuration and minimize the energy consumption of the complete transportation system.

EnerGplan conducts an overall analysis of transit system performance to predetermine the optimal mode of transit system operation. The analysis includes:
- Fleet performance
- Train speed profiles
- Power distribution system load flows
- Effects of onboard and wayside energy storage devices
- Train schedules
- Train routing

EnerGplan also provides an analysis of the optimal power system configuration, such as location, rating and setting of energy storage devices that minimize energy consumption.

The flexibility of this software allows the user to model virtually any transit system of any complexity.

Operating cost reduction and power system design optimization

Now more than ever, transit authorities and system operators are compelled to find ways to reduce transit system capital and operating costs. Many technologies available on the market today claim to achieve significant energy reductions, but can be very expensive and largely ineffective if used inappropriately. In certain applications such devices may even lead to degradation of transit system performance. *EnerGplan* provides the means to evaluate these technologies to determine their effectiveness and their impact on system operation.

EnerGplan has the capability to simulate different power distribution system configurations with various energy-saving scenarios to determine the optimum solution. For example, it clarifies whether the onboard energy storage or wayside energy storage offers the optimum energy saving for a specific system, by simulating both configurations to determine the optimum solution from a system performance, capital cost and energy reduction perspective. It can also calculate the CO_2 reduction for different scenarios.

EnerGplan Main Features

Graphical environment

EnerGplan employs an easy-to-use graphical environment to:

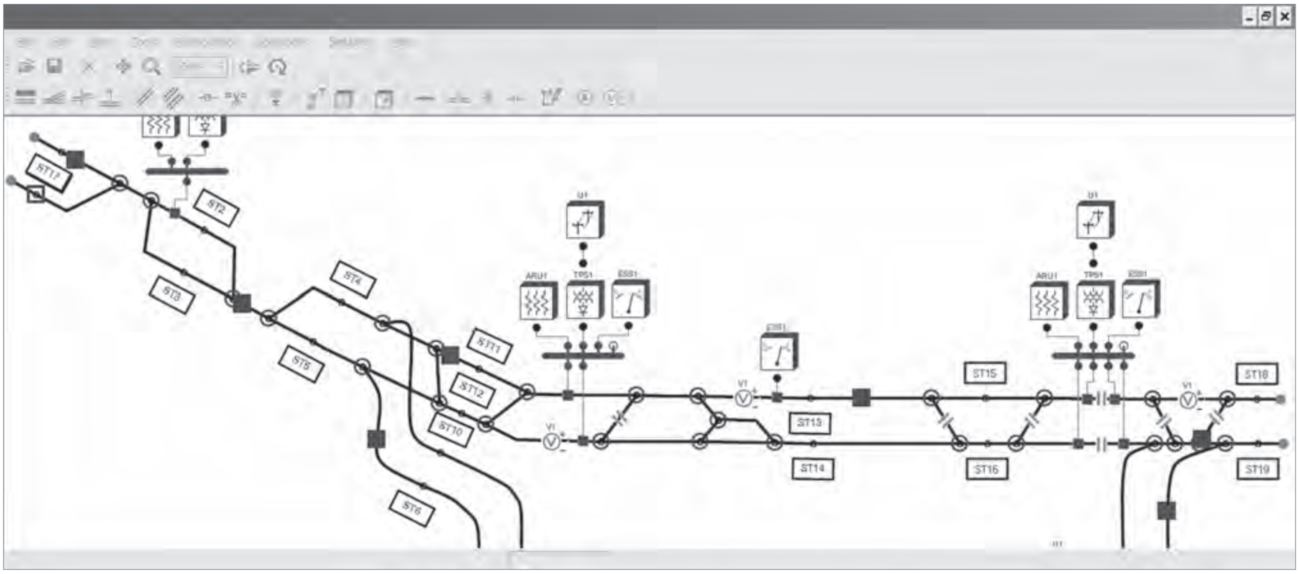
- Construct any track plan using the available basic track building blocks
- Construct any power system using the basic power distribution building blocks

The graphical environment provides the ability to:

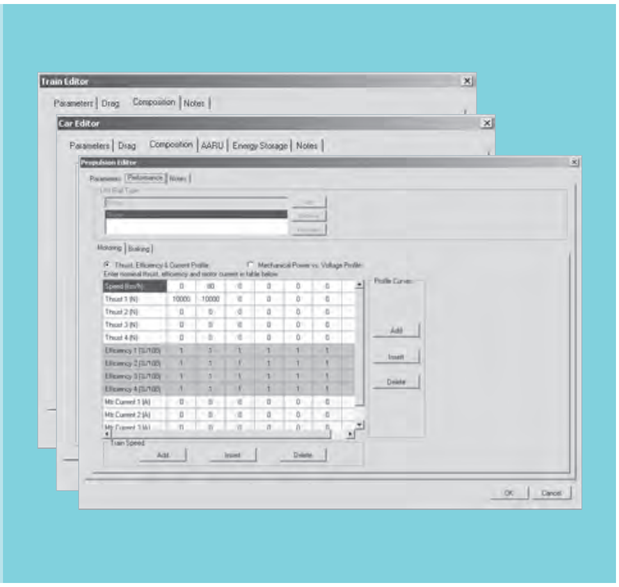
- Superimpose a guideway on an aerial or other map
- Edit parameters of any object using a double click
- Zoom in/out, pan, add grid lines, mouse lines and curve features
- Flip, rotate or delete any object

Guideway editor

EnerGplan is capable of simulating multiple train routes operated at different headways for the same studied case. The chainage equality feature allows the user to easily input guideway data as it is received from civil engineers without manual pre-processing.



Graphical environment


Train Editor
Parameters | Drag | Composition | Notes
Car Editor
Parameters | Drag | Composition | AARU | Energy Storage | Notes
Propulsion Editor
Parameters | Performance | Notes
Motoring | Braking
Thrust, Efficiency & Current Profile
Mechanical Power vs. Voltage Profile
Profile Curves
Add
Insert
Delete
Train Speed
Add
Insert
Delete
OK
Cancel

Enter nominal thrust, efficiency and motor current in table below

Speed (km/h)	0	80	0	0	0	0
Thrust 1 (N)	10000	10000	0	0	0	0
Thrust 2 (N)	0	0	0	0	0	0
Thrust 3 (N)	0	0	0	0	0	0
Thrust 4 (N)	0	0	0	0	0	0
Efficiency 1 (%/100)	1	1	1	1	1	1
Efficiency 2 (%/100)	1	1	1	1	1	1
Efficiency 3 (%/100)	1	1	1	1	1	1
Efficiency 4 (%/100)	1	1	1	1	1	1
Mtr Current 1 (A)	0	0	0	0	0	0
Mtr Current 2 (A)	0	0	0	0	0	0
Mtr Current 3 (A)	0	0	0	0	0	0

Rolling stock editor

Rolling stock editor

EnerGplan is not limited to any specific type of train or transit technology. The generic input feature allows the flexibility to simulate multiple train types operating simultaneously on one or more user-definable routes. *EnerGplan* can be used to simulate everything from the largest metro system to the smallest people-mover application.

The rolling stock editor consists of train editor, car editor, and propulsion editior. It is capable of modelling onboard energy storage as well as onboard resistors.

Electrical network editor

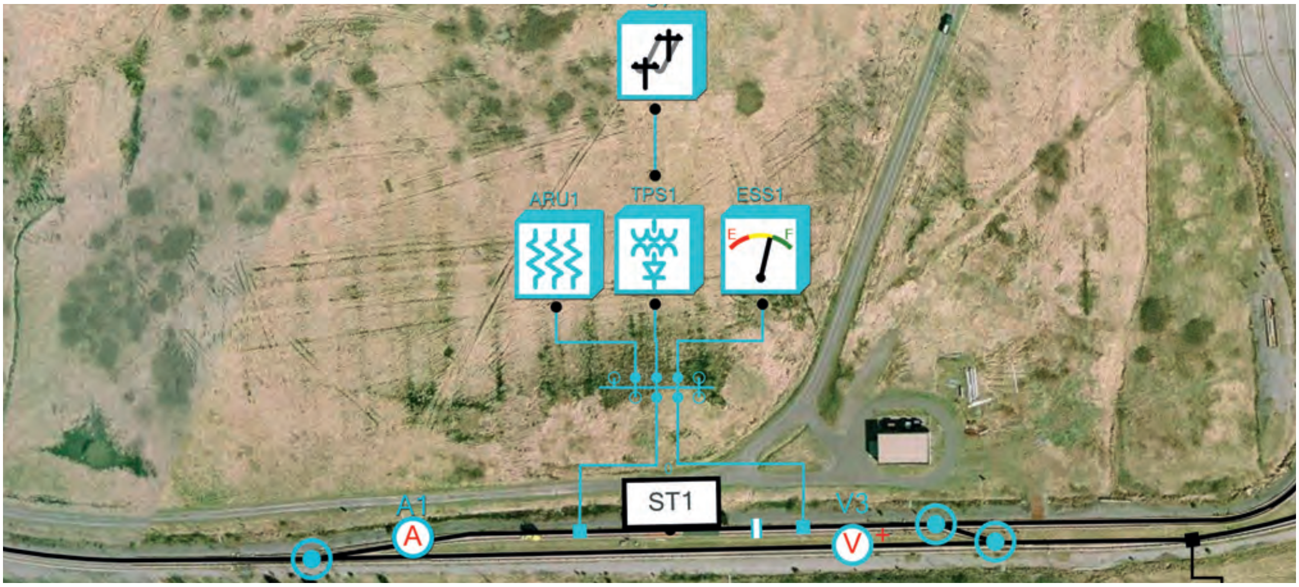
EnerGplan is capable of modelling:

- Traction power substations (TPS)
  - DC TPS: rectifier, controlled rectifier, controlled rectifier with inverter
  - AC TPS: normal transformer, autotransformer, booster transformer (future)
- Wayside energy storage – used to reduce energy consumption and for voltage regulation applications
- Wayside resistor banks – used to dissipate regenerated energy if the power system is non-receptive
- Power rail, catenary and running rail to distribute electrical power to the vehicles (with local and global resistance/impedance editing)
- Utility substations
- Feeder cables (including length, size of cable/feeder, resistance/km for both positive and return)
- Busbars and feeder cables (allows interconnection of any number of feeder cables)
- Power rail gaps (gaps can be in either positive, negative or both power rails)

EnerGplan Capability

Dynamic load flow modelling

Interactions among multiple trains are included in the load flow analysis, thus allowing simulation of actual system performance and providing an accurate power supply and distribution design. Traditional load flow models employ a model where trains are simulated independently of the power system. *EnerGplan* models both the train and power system simultaneously and interactively so that the effect of power system voltage drops on train performance can be determined.



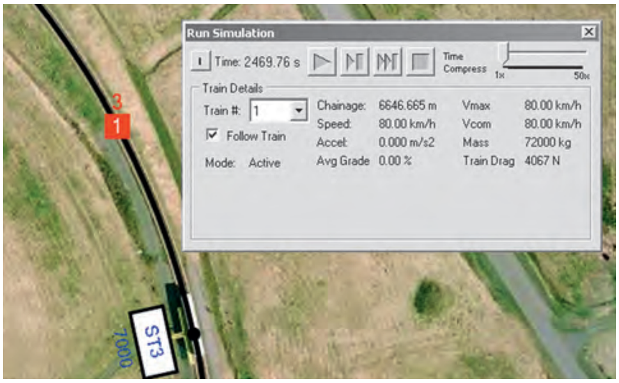
Electrical network editor

EnerGplan Simulation Tool

EcoActive Technologies

Graphical visualization

The dynamic train display allows monitoring of any chosen train operating on the guideway, displaying its location and other pertinent operational data. The graphical visualization tool is a unique and informative way to demonstrate fleet operation with the option of demonstrating power supply and distribution system behaviour. The instantaneous current and voltage of selected traction power substations, busses or feeders can be displayed, as well as the current stored or released from any energy storage unit.



Time: 2469.76 s

Train Details

Train #: 1

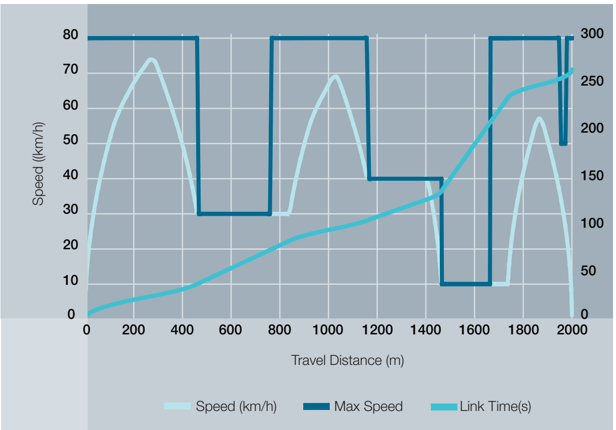
☑ Follow Train

Mode: Active

Chainage: 6646.665 m
Speed: 80.00 km/h
Accel: 0.000 m/s2
Avg Grade 0.00 %

Vmax 80.00 km/h
Vcom 80.00 km/h
Mass 72000 kg
Train Drag 4067 N

Train monitoring



Train run results

ECO4 – Energy, Efficiency, Economy and Ecology
EnerGplan **forms part of Bombardier's** ***ECO4**** **environmentally friendly technologies. Addressing the growing challenges among operators to reduce Energy consumption, improve Efficiency, protect the Ecology while making sense Economically,** ***ECO4*** **is the concrete validation of Bombardier's declaration –** ***The Climate is Right for Trains****.**

EnerGplan outputs and results

Operation analysis and load flow results are generated as text files and visualized using a graphical utility add-on. The text outputs are divided into summary and detailed reports for both train performance and load flow analysis.

The flexibility of the graphical utility allows the user to generate any kind of graph needed to illustrate train performance and/or power system design.

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Bombardier Transportation
Schöneberger Ufer 1
10785 Berlin, Germany

Tel +49 30 9 86 07 0
Fax +49 30 9 86 07 2000

www.bombardier.com

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Energy efficient and overhead contact line free operation of trams

Dr. Michael Meinert, Dr. Karsten Rechenberg, Dipl.-Ing. Peter Eckert
Siemens AG, Industry Mobility Electrification

ABSTRACT

Today's innovative technologies for Railway Electrification and Rolling Stock enable an energy efficient operation of railway vehicles supplied by the overhead contact line. In the case there is no possibility to recover the braking energy, an onboard energy storage unit allows absorbtion of this energy for re-use. Therefore the energy consumption and the emission of "Greenhouse gases", e.g. CO_2, can be reduced significantly. But a second operation mode realized by onboard energy storage unit is possible – the operation of such equipped rail vehicles on tracks without overhead contact lines. So this increasingly arising requirement of customers due to aesthetical, environmental or operational reasons can be satisfied by the technology of onboard energy storage units.

1 Motivation

The spread of urbanization calls for attractive, environmentally-friendly and economic transportation solutions in order to ensure the competitiveness and appeal of urban regions in the long term.

Today's innovative technologies for Rolling Stock and Railway Electrification afford an energy efficient operation of the complete railway system. Here the major task is to minimize the power consumption of the transportation system and the emmission of "Greenhouse gases", e.g. CO_2. For this purpose it is necessary to consider the overall integration of all parts of the whole railway system – the stationary traction power supply (Railway Electrification), the railway vehicles (Rolling Stock) and the railway network – as well as the operational concept of all mentioned parts [1].

1.1 Why onboard energy storage units

The focus of more arising customer's requests is to reduce energy consumption as well as to cross track sections, where an **O**verhead **C**ontact **L**ine (**OCL**) is not useful or not possible, e.g. at street crossings or historical or picturesque sites. Both of these requests can be met by the use of onboard energy storage units [2, 3].

The first advantage of these onboard energy storage units is to recover the braking energy if there is no possibility to return it via the OCL instead of dissipating the energy into the braking resistor. The recovered energy can be reutilized afterwards, e.g. for acceleration of the vehicle.

The second advantage realized by onboard energy storage units is the operation of such equipped vehicles on tracks with catenary-free sections or on tracks without OCL.

So this more and more arising requirement of customers due to operational or even aesthetical reasons can be satisfied by the technology of onboard energy storage units.

Due to this, power supply by an onboard energy storage unit is not visible at the environment. These kinds of power supply are called "**N**on-**V**isible **C**ontact line (NVC)" technologies.

These energy storage units may be based on the technology of double layer capacitors as one possibility. Such systems fulfill these requests combining the following advantages on rail vehicles:

- reutilization of braking energy,
- decrease of energy consumption and therefore energy costs,
- reduction of peak power and
- operation on OCL-free distances and therefore saving of electrification costs.

This will be explained for a tram as one example.

2 Operational modes

The use of onboard energy storage units allows several operational modes such as:

1. Energy optimized operation
2. Voltage stabilizing operation
3. OCL-free operation and
4. Diesel-engine boost operation (if applicable).

2.1 Mode of Energy optimized operation

In this **E**ner**g**y **O**ptimized (**EgO**) mode the vehicle operates at the OCL. The braking energy, which is partly recuperated or dissipated into heat, will be stored in the onboard energy storage unit consisting e.g. of double layer capacitors. This stored energy will be reused for acceleration of the vehicle or for the auxiliary power supply, e.g. for air conditioning. With this application energy savings up to 30 % are possible.

Fig. 1 and Fig. 2 show, that the current from the OCL is lower than the traction and auxiliary current due to the current from the onboard energy storage unit. With this application the peak current taken from the OCL power supply can be reduced. Depending on the power or energy supply contract this may reduce the energy-costs, too.

2.2 Mode of Voltage stabilizing operation

The use of onboard energy storage units wihle operating the vehicle at the OCL has a significant influence on the peak-load and so on the voltage drops and peaks of the supply-voltage. The onboard energy storage unit reduces the power taken from the OCL during acceleration and the power recuperated to the OCL during braking. This causes a reduction of the current transmitted by the OCL and so the supply-voltage is stabilized.

The application ranges up to a DC-link voltage of 750 V DC (optional up to 1500 V DC).

Experiences in revenue operation for stationary wayside energy storage units are gained since years [1] and can be applied for onboard energy storage units, too.

2.3 Mode of Non-Visible Contact line (NVC) operation

The stored energy can be used to cross OCL-free sections. These sections may be e.g. a street-crossing, where the OCL's are difficult to install. Another application is the possibility to omit the OCL at historical or picturesque sites due to aesthetic or architectural requests.

Fig. 3 and 4 show the NVC-operation without OCL.

At this application the whole power demand of the vehicle for traction and for auxiliaries is taken from the energy storage unit. The vehicle is accelerated with maximal driving force up to the usual speed (here 35 km/h). Than the traction power is switched off and the tram rolls till it is decelerated with maximal braking force to stop at the station. During the rolling the auxiliaries are supplied by the energy storage unit. This is the most economic operation. During dwell time the energy storage unit is recharged using an external power supply at the station. The time for recharging the storage unit to maximal energy content (approximately 10 s) is normally shorter than the dwell-time (approximately 20-30 s).

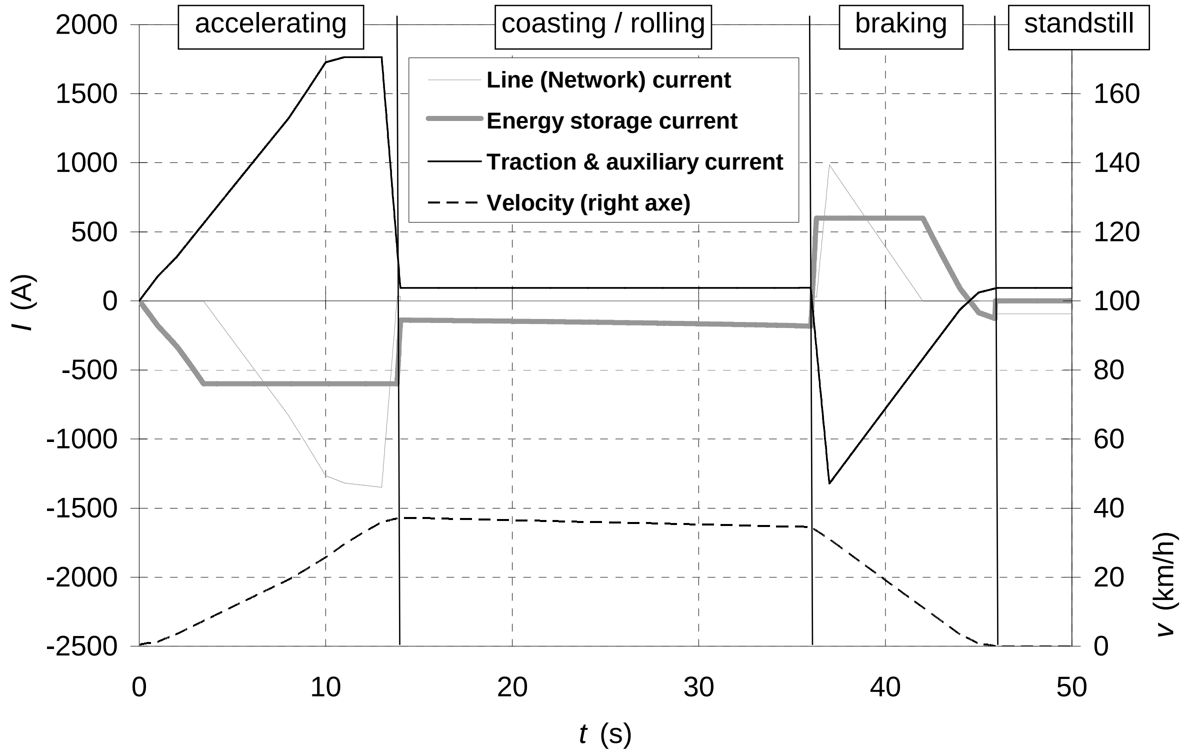

Fig. 1: **Currents during energy optimized operation at power supply by the OCL**

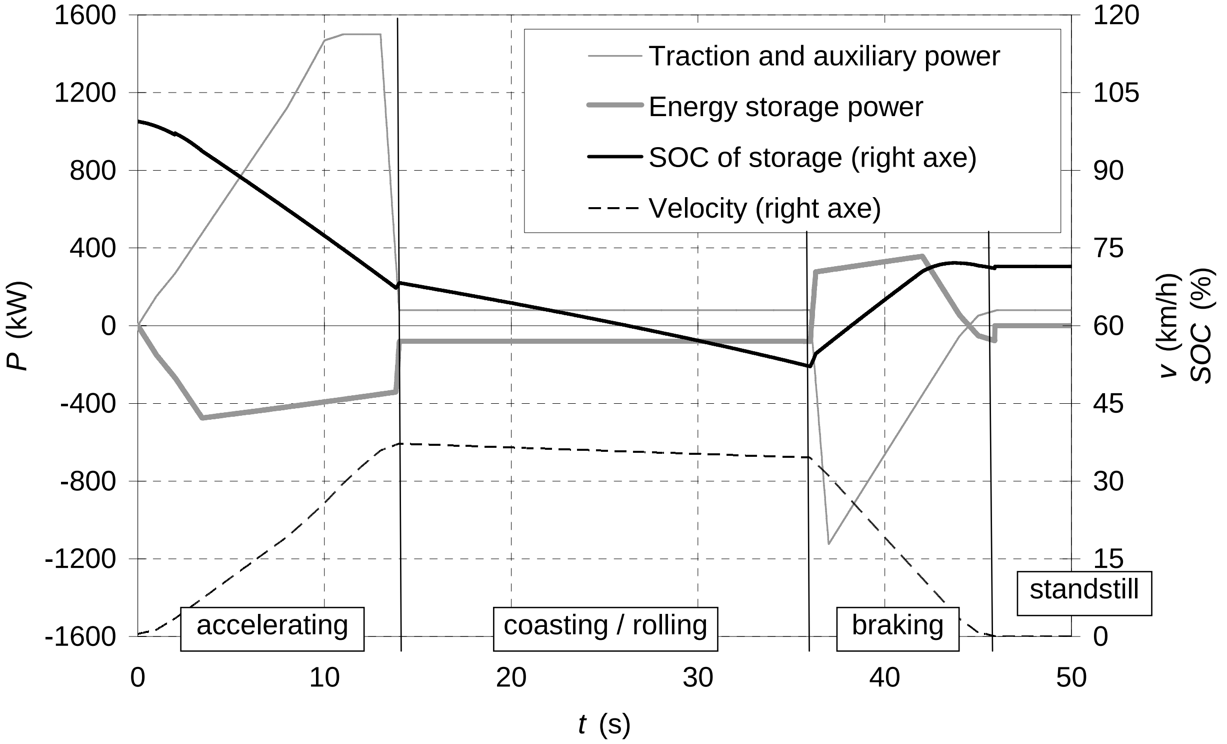

Fig. 2: **Power and state of charge (SOC) of energy storage unit during energy optimized operation at power supply by the OCL**

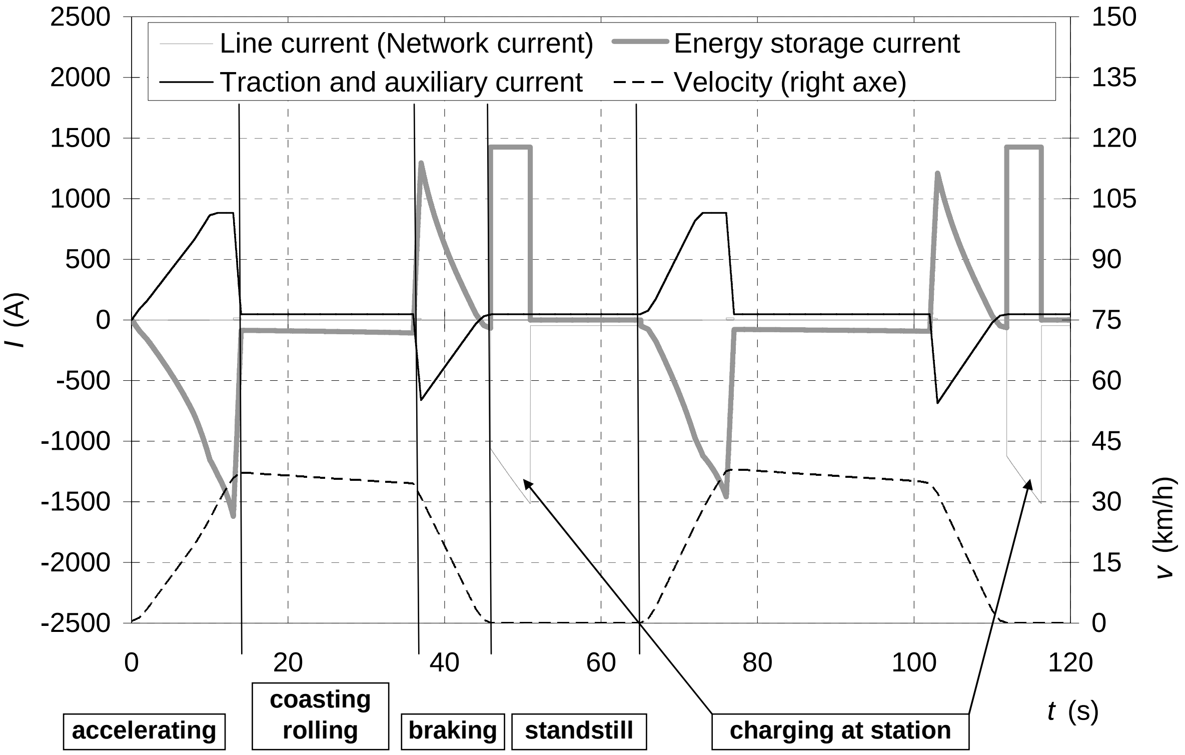

Fig. 3: **Driving without OCL, but with recharging of the onboard energy storage unit at stations during dwell-time: currents and vehicel's velocity**

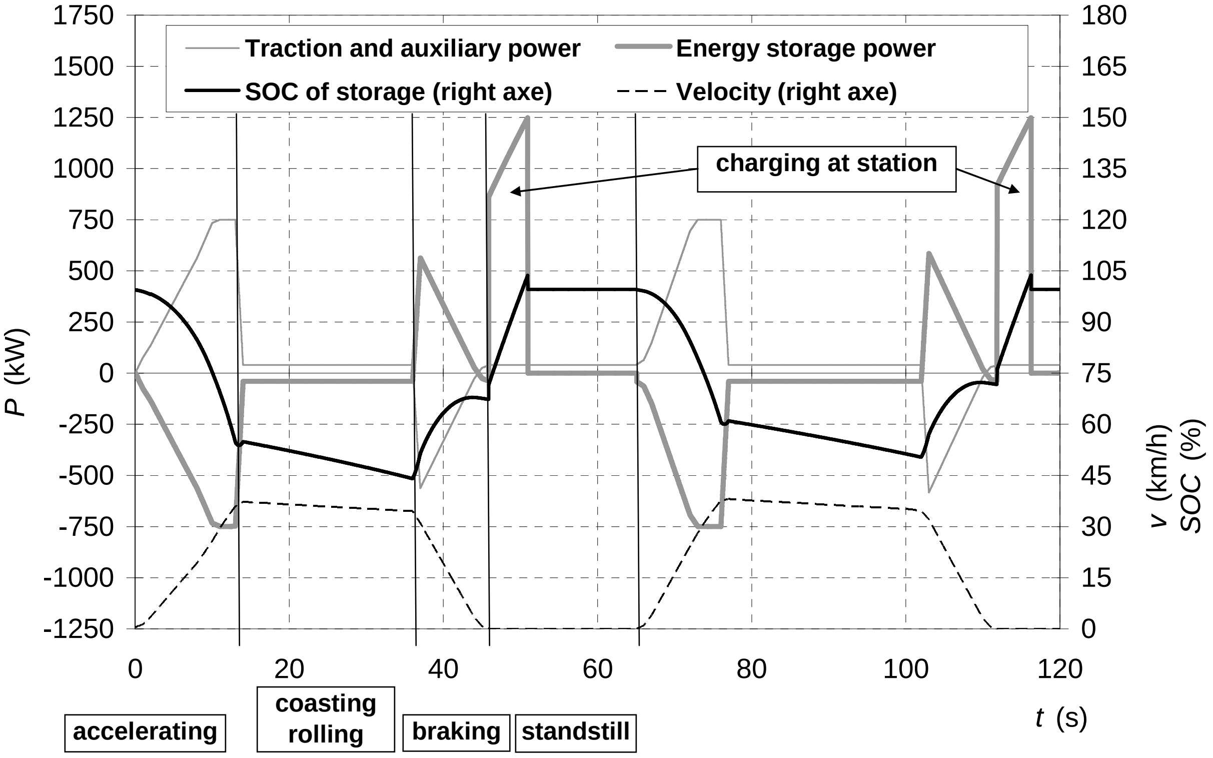

Fig. 4: **Driving without OCL, but with recharging of the onboard energy storage unit at station during dwell-time: power, vehicle's velocity and SOC**

2.4 Advantages when used at diesel hybrid vehicles

The operation of onboard energy storage units has to be coordinated with the traction power systems of the vehicle. Used in combination with a diesel engine the energy storage unit can improve the traction system in several aspects [4]:

- Enhanced efficiency of the traction-power source (diesel engine, fuel cell)
- Booster mode, increased acceleration, shorter travel times
- Advantages of a diesel engine (large range) combined with the advantages of an electric motor (emission-free)
- Downsizing of the diesel engine
- Reduced fuel consumption and emission of pollutants such as CO_2 and NO_X
- In some sections, emission-free operation (e.g. in railway stations).

3 Integration of the energy storage units into the traction system

The onboard energy storage units have to be integrated into the vehicle and into the traction system as well. The energy storage units, especially the double layer capacitors, have a system-voltage which depends on the stored energy. They can not be connected directly e.g. to the intermediate DC-link. The voltage of the energy storage unit has to be increased to the voltage of the DC-link by use of a DC/DC-chopper or Buck-Boost-converter.
To integrate this converter there are two different concepts which can be used each having its advantages depending of the configuration of the system.

3.1 The converter

The traction converter normally consists of a 3-phase pulse-width-modulation converter which forms a 3-phase, amplitude- and frequency-variable supply for the traction motors. The Buck-Boost-converter works nearly in the same way and with the same hardware. The voltage of the DC-link is pulse-width-modulated or ‘chopped’ to the chopper choke causing an adjustable current which charges or discharges the energy storage unit.
The design of the converter, the chopper choke and the control of the DC/DC-chopper are in accordance with the requirements for the voltage, efficiency and power needed.

3.2 The integrated concept

The traction converter can easily extended by an additional phase module which can be used for the chopper function. This added phase module is totally integrated into the traction converter-topology, using the same control and cooling devices. Therefore the assembly is very compact.
The main characteristics of this integrated concept (see Fig. 5) are:

- Energy storage unit directly connected to the intermediate DC-link of the traction converter
- no additional line choke needed and
- one energy storage unit per traction converter possible.

The chopper choke and the switch can also be integrated into the traction container or into the storage container. This solution is particularly suitable for new-built applications where the traction converter can be designed for this purpose.

3.3 The independent or ‘stand-alone’ concept

In many applications the energy storage unit may be added to an already existing traction system. In these cases the independent or ‘stand-alone’ concept will be the most suitable.

In this concept a complete buck-boost converter with its own control system, line- and chopper-choke, DC-link and a main switch will be assembled in addition to the traction converter to commute the energy from the traction system to the storage system and vice versa.
The main characteristics of this integrated concept (see Fig. 6) are:

- Energy storage unit connected to the DC-link of the vehicle
- additional line choke needed and
- several energy storage units per DC-link possible.

The chopper can be mounted in a separated container or may be integrated in the storage container. The advantage of this concept is, that it is totally flexible and scalable to most applications.

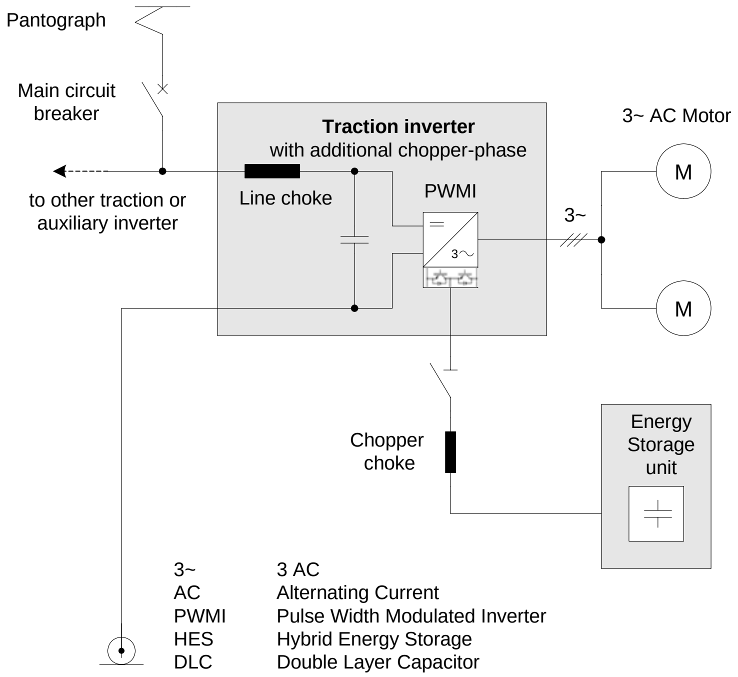
Pantograph
Main circuit breaker
to other traction or auxiliary inverter
Traction inverter
with additional chopper-phase
Line choke
PWMI
3~
3~ AC Motor
M
M
Chopper choke
Energy Storage unit
3~ 3 AC
AC Alternating Current
PWMI Pulse Width Modulated Inverter
HES Hybrid Energy Storage
DLC Double Layer Capacitor

Fig. 5: **Integrated concept for the energy storage unit**

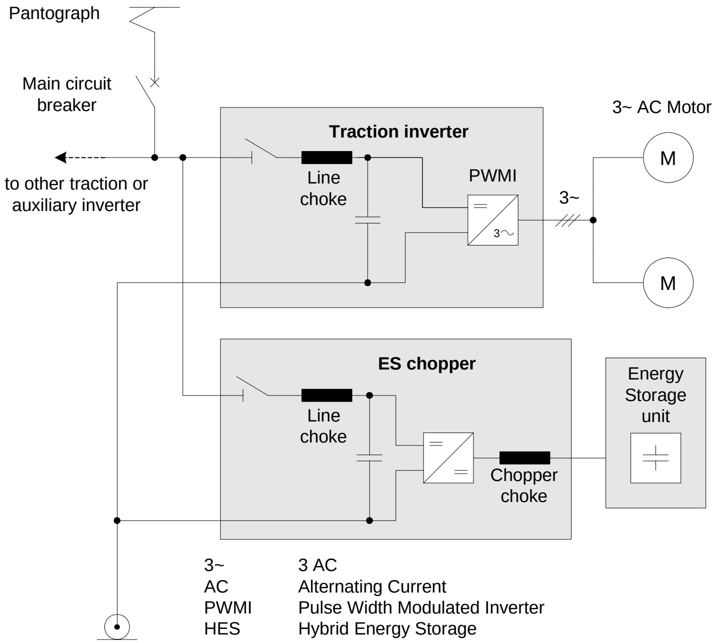

Fig. 6: **Independent concept for the energy storage unit**

3.4 The energy storage unit

Today different kinds of onboard energy storage units are used at transportation applications. The most common storages are the flywheel, the battery and the double-layer-capacitor, so called UltraCaps, BoostCaps, SuperCaps, etc.

3.4.1 The double-layer-capacitor (DLC)

DLC's are capacitors with a huge amount of capacity (e.g. 3,000 to 5,000 F). These capacitor cells are arranged to modules and the modules can be assembled to an energy storage unit, which is especially designed to the requirements of the application (see Fig. 7). Due to this modular construction the energy content and the system voltage are flexible within a certain range as well as the maintenance can be easily carried out. For safety reasons a thermal and electrical supervision of the capacitors is highly integrated in each module.
The DLC's are suitable for the use on railway vehicles due to their characteristics and operating behavior. The main features are the high efficiency, the high dynamic for load transfer and the cycle-stability (more than 1 million cycles). Moreover DLC's are deep-discharge suitable, maintenance-free and environment friendly.

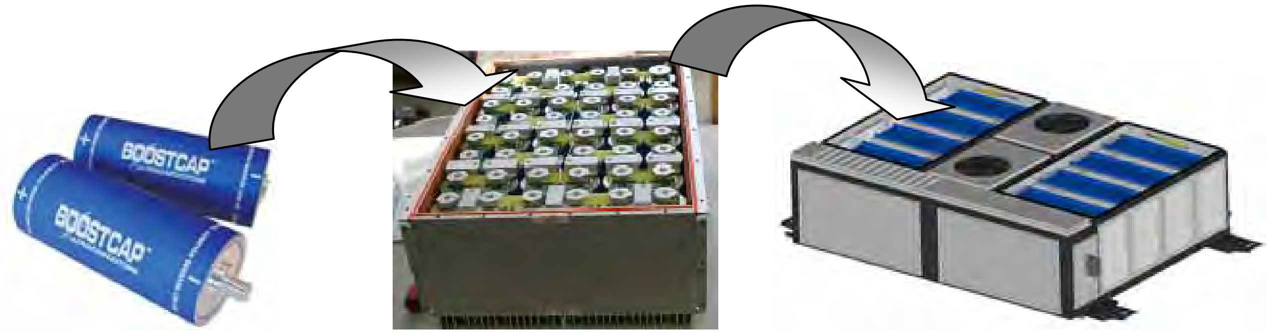

Fig. 7: **Configuration from DLC-Cells to module, assembling of modules inside the container and container for mounting on roof of the vehicle**

The comprehensive tested DLC-Modules assembled into a roof-mounted container are certificated by the German TÜV Süd for use on passenger transportation systems, e.g. trams and is homologated according the BOStrab (German Construction and Operating Code for Tramway).

3.4.2 Batteries

Today there are only few providers on the market, which can deliver approved technology for traction batteries. The today most suitable batteries are NiMH-batteries (see Fig. 8). Lithium-Ion (Li-Ion) batteries are still under development because safety and homologation issues for Li-Ion batteries have to be solved for use on railway applications.
There is a deciding difference between the two kinds of energy storage technologies, DLC's and Batteries: the energy content and the maximal power of the device.
DLC-energy storages have low energy content, e.g. 1 or 2 kWh, but can deliver or take this energy within a very short time, e.g. 10 … 15 seconds, so they can provide a high power (e.g. 600 kW) for a short time.
Batteries have high energy content, e.g. 15 to 20 kWh, but can deliver or take only a low power (e.g. 80 kW) for a long time, e.g. 10 to 15 minutes.
While DLC-energy storages mostly are used in energy-saving or voltage-stabilization mode, the combination of the two different behaviors of the DLC- and battery-storages provides a unique opportunity to realize a NVC-operation of a vehicle between singular charging stations.

Fig. 8: **Example of a traction battery (Saft Batteries, France)**

4. Hybrid concept or Hybrid Energy Storage (HES)-system

4.1 Concept of the HES-system in general

The DLC and the battery are able to complement each other in an optimized way. The DLC provides the high traction power needed for a short time for acceleration of the vehicle. The battery delivers the energy needed for traction during coasting and to supply the auxiliary power as well. During braking the DLC can absorb the most part of the braking energy.
This leads to the so called '**H**ybrid **E**nergy **S**torage' **HES**-system.
Fig. 9 shows the state of charge of the two energy storage units DLC and battery. Starting at a station, where the vehicle has a contact to the external power supply, the storages will be charged to maximum energy content. During the acceleration phase the energy is taken primarily from the DLC's. The DLC-storage is rated to adequate energy-content and power for this phase. After the acceleration the vehicle needs significantly less power, which can be delivered by the battery. During braking the energy is absorbed by the energy storage system. The energy needed during the dwell time (e.g. for air-conditioning) and if necessary to charge the energy storage system completely will be supplied by a stationary charging unit.

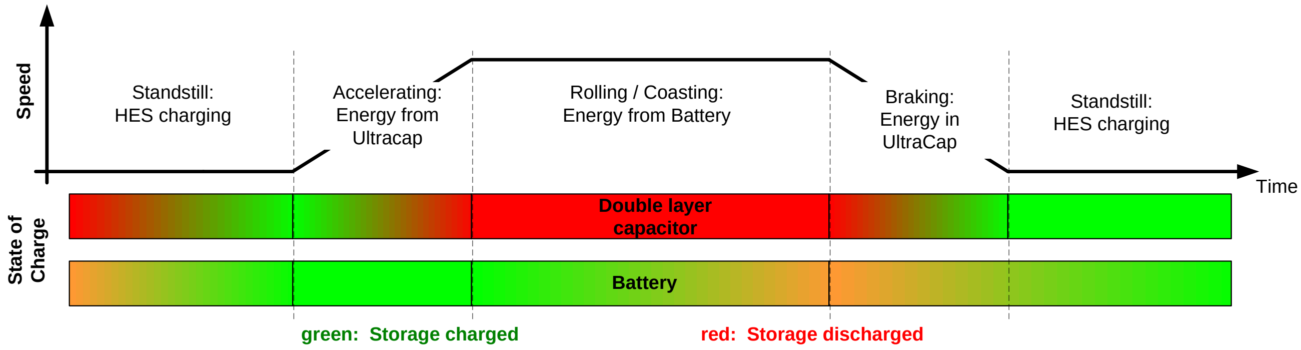

Fig. 9: **General function of the HES-system**

4.2 Concept of the Local Charging Unit (LCU)

Charging of the energy storage units or systems during stops can be done by electrical contacts e.g. via the pantograph or a third-rail-contact. These LCU can be implemented at the passenger stations or also at special locations, where a recharge may be necessary, e.g. at traffic lights.
The recharging of the energy storage units will be done during normal dwell time, e.g. 20 to 30 s. For example, for a Combino Plus vehicle a DLC-energy storage unit with an energy-content of 2 kWh will be used. A complete reload of these 2 kWh will take 18 s with a power of 400 kW.
The NiMH-battery should be used within a range of 10 % deep of discharge (DoD) to ensure a proper lifetime. So the battery has a nominal energy content of 18 kWh, where about 1.8 kWh will be used in cyclic operation.
The next advantage of the HES-system is, that in case of a hesitation or unforeseen stops at OCL-free sections, where the vehicle needs more energy than scheduled, the battery has some kind of back-up energy to ensure, that the vehicle can reach the next charging station. Even in case of failure the energy content of the battery is sufficient to cross a long distance without any external power supply. The lower discharge of the battery will decrease the lifetime, but this can be neglected if this emergency-operation occurs only infrequently.

5. Forecast and summary

To study the behavior of the HES-system and the interaction of all components of the energy storage system a stationary system test will be performed. This system test comprises a standard traction container, equipped with an additional DC/DC-chopper, chokes and switches, connected with a DLC-energy storage unit and a battery unit. Two traction motors to simulate driving operation will be connected to the traction inverter as well. At this system test all kinds operations of the vehicle and the energy storage systems and also most of failure scenarios can be simulated and tested.
These tests will incorporate the useful operation modes:

- Energy optimized operation
  The savings of energy by the use of the HES-system will be measured and analysed.
- Voltage stabilizing operation
  The reduction of peak-load of the vehicle will be verified and evaluated.
- Non-Visible Contact line operation
  The NVC-operation will be simulated by disconnecting the main power supply and simulation of driving without external energy for certain times.

These tests will be concluded within year 2008. In addition to the electrical system test several mechanical and thermal tests will be performed to check the endurance strength of the used components.
Studies regarding energy storage units onboard of trams at tracks with high duty cycles indicate a meaningful use of such units. The comparison of different energy storage technologies points out the double layer capacitor as an appropriate energy storage technology to store energy for high power/short time applications and batteries as an appropriate energy storage technology for low power/long time applications.
The combination of the DLC with a battery system can ensure the optimal performance for an OCL-free operation. Most applications may be mixed operation, where sections with catenary will alternate with sections, where the OCL is not useful or undesired. So this concept allows an energy optimized operation at the OCL and the possibility to arrange the route network with OCL-free sections.
Even at power supplied networks the use of energy storage units can save up to 30 % depending on all circumstances during the operation of the whole tram system. Also in the case of recuperating it is meaningful to keep the braking energy onboard as much as possible.
The investigation regarding OCL-free distances leads to the result that the average distance for LRT-systems of 300 m up to 500 m can be crossed by onboard energy storage units easily. The charge of these storages can be done during the dwell time at stations. If larger distances have to

be crossed or operational conditions lead to an insufficient charging of the energy storage unit, stationary charging can be done along the track, e.g. at traffic lights. At this a power supply in the meaning of small power supply stations has to be installed in a range of 300 kW up to 500 kW to complete the charge or to support the power demand of the tram.

The homologation was reached by the use of modules and derived measures for the design of the energy storage unit given by the TÜV Süd Group. The parallel conducted studies as well as the successful tests during the development of the energy storage unit support this homologation according the BOStrab (German Construction and Operating Code for Tramway).

An investigation of the complete railway system seems to give different answers regarding the best approach to consume as little energy as possible. Various recommendations can be attractive for the operators, reflecting the increasing operator's requests on reduction of energy consumption and therefore of CO_2-emission.

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Biographical note

Michael Meinert (37) graduated in electrical engineering, Electrical Railway Systems, from Dresden University of Technology, Germany, in 1995 and received his doctorate in electrical engineering from Darmstadt University of Technology, Germany, in 2006. His employment experience included the Siemens AG, Mobility (former Transportation Systems), Erlangen since 1995 and the Darmstadt University of Technology from 2001 to 2004. He is currently the Head of the group for OCL-free systems at the Siemens AG, Mobility.

Karsten Rechenberg (43) graduated in electrical engineering, Electrical Railway Systems, from Dresden University of Technology, Germany, in 1990, received his doctorate in electrical engineering from the Technical University of Chemnitz, Germany, in 1994 and received his State doctorate in power engineering from the Technical University of Cottbus, Germany. From 1990 to 1994 he was a project manager at the Technical University of Chemnitz and from 1994 to 2000 chief engineer at the Technical University Cottbus. In 2000 he joined the Siemens AG, Transportation Systems, Erlangen. Since 2001, he has been in charge as a project manager.

Peter Eckert (43) graduated in electrical engineering, Electrical Power Engineering, from Aachen University of Technology, Germany in 1991. He started his employment at the Siemens AG, Power Generation, Erlangen in 1992 as project engineer for excitation systems for power generators. In 2001 he joined the Siemens AG, Transportation Systems, Erlangen and has been in charge as R&D project manager at the Group Technology. Since 2007 he is project manager for the electrical design for OCL-free systems at the Siemens AG, Mobility.

Energy saving by onboard storage

学术搜索

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SPEEDAM 2006
International Symposium on Power Electronics,
Electrical Drives, Automation and Motion

Energy saving by on board storage

F. Giorgetti*, L. Pastena* , A. Tarantino* , F. Velotto*
(*) Research Department AnsaldoBreda , Via Argine n 425 , Naples, (*Italy*)

***Abstract*— The Ansaldobreda Research Department has carried out a study and experimentation on an innovative energy storage system consisting of supercap's modules installed on an electrical vehicle. Since the supercap's have very short charge time (few seconds), it is possible to store high energy gradients. Therefore their application allows the optimisation of energy consumption as well as the achievement of an high energy recovery during the braking phase. The energy stored during the transients can be utilised during the starting phase until the cruising speed is reached. In this way, the batteries are used only for the running phases, also determining their life cycle improvement. Test on the small electrical vehicle has shown that the energy recovered in the braking phase is about a 30% of the starting energy. This energy storage system can be applied to vehicles as Electrical buses, Hybrid Vehicles or Trams.**

***Index Terms*—Storage systems, Hybrid electrical vehicles**

I. NOMECLATURE

Imx cd = Maximum current of charge discharge
EM =Energy Management System

II. TECHNICAL WORK

In the Research Centre of ANSALDOBREDA an innovative on board storage system has been studied and experimented. This system is made by a module of supercapacitors issued on a electric small vehicle.

The use of the supercap's allows to optimise the energetic consumptions and to get an elevated energy recovery in the braking phase.

The tests have been performed with an energy management system that checks the state of charge of the supercap's, allowing the alone operation of it during the transitory phases (starting/braking).

In comparison to the batteries, the supercap's have very brief times of charge (order of the seconds) and therefore elevated gradients of energy stored. It's possible, therefore, to recharge the supercap's to every least braking operation, during the urban cycle with a smaller consumption of the mechanical parts.

The stored energy during the transients can be utilised during the starting phase, until the cruising speed is reached. In this way the batteries are used only during the phases of running and this also guarantees a greater time of life of these last.

With this type of application, an energy saving around 20 – 30% is expected.

This system of energy storage can be employed on vehicles used in the urban and regional service.

Immediate application:

- electric bus, to increase the autonomy of march or to reduce the batteries weight;
- hybrid vehicles as diesel-electric, to allow a strong reduction of the battery package.

MAIN TECHNICAL DATA:

Specific Power	476 W/kg
Imx cd (25 °C)	400 A.
Specific Energy	2.4 Wh/kg
Module weigh	(28kg ultracap+20kgs carpentry and connections) 48 Kg

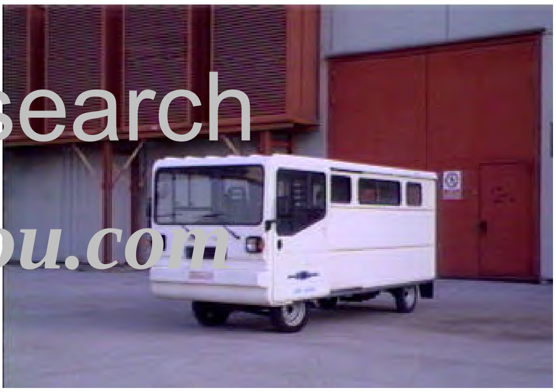
Fig. 1. Vehicle whose characteristics are reported in tab. I.

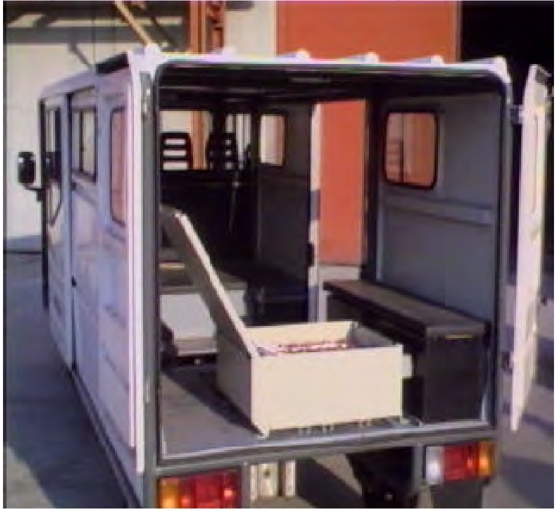
Fig. 2. Storage location inside the vehicle

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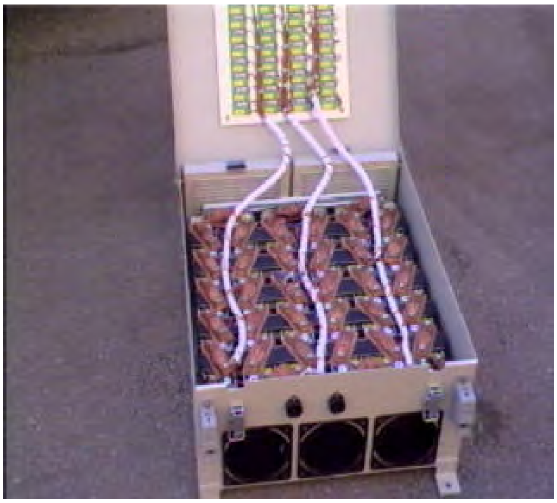

Fig. 3. Storage system of the vehicle

TABLE I
CHARACTERISTICS OF THE VEHICLE

Feeling	96 Vccs
Storage system batteries	15 kWh
Ultracap	70 Wh
Driving system	Chopper + dc motor

III. TRACTION DIAGRAM (SEPARATED SYSTEM)

A. Separate energy sources

The solution with a separate energy source requires a complication due to the presence of the switches to select the energy sources and a PLC for their management.

During a complete duty cycle (starting and braking operation) the energy recovered in the braking is around 30% of the energy spent in the starting phase.

Specific test has been performed in the road flat area of the Research Department in ANSALDOBREDA Naples.

In these conditions, after some cycles, the supercap's contribution become negligible and the running proceeds on battery only. During the braking on slopes, the proposed system may allow an energy storage such as to guarantee multiple consecutive cycles.

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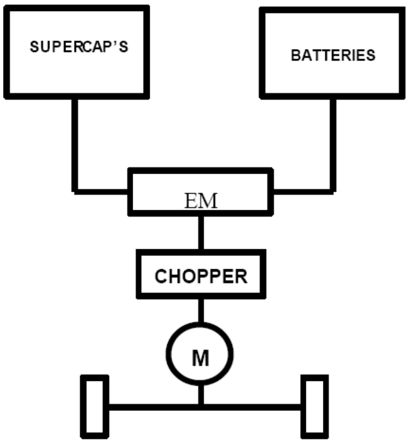

Fig. 4. Traction diagram for separated system

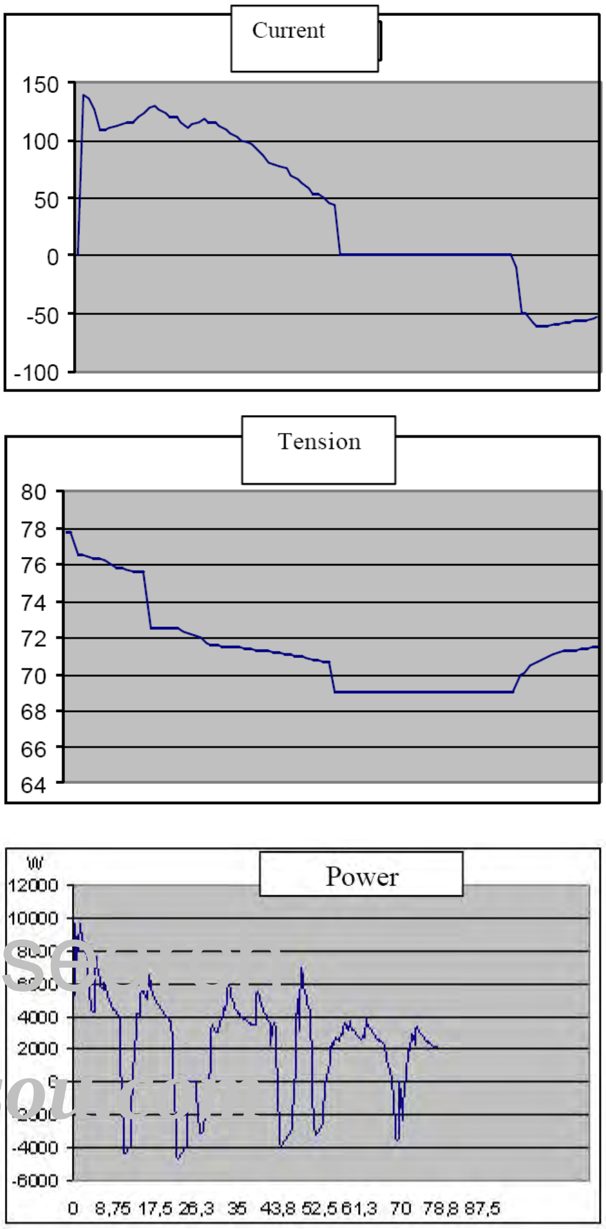

Fig. 5. Current, voltage and power for separated system

IV. TRACTION DIAGRAM (MIXED SYSTEM)

A. Separate energy sources

The solution with a separate energy source requires a complication due to the presence of the switches to select the energy sources and a PLC for their management.

During a complete duty cycle (starting and braking operation) the energy recovered in the braking is around 30% of the energy spent in the starting phase.

Specific test has been performed in the road flat area of the Research Department in ANSALDOBREDA Naples In these conditions, after some cycles, the supercap's contribution become negligible and the running proceeds on battery only.

During the braking on slopes, the proposed system may allow an energy storage such as to guarantee multiple consecutive cycles.

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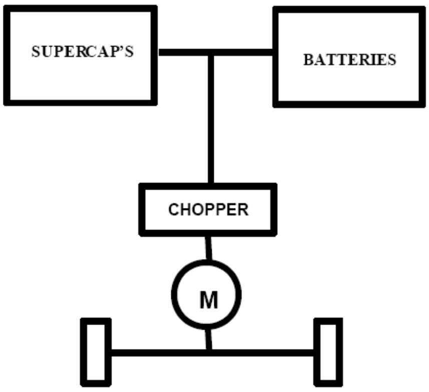

Fig. 6. Traction diagram for mixed system

B. *Mixed energy source*

The energy source consisting of batteries connected in parallel with supecap's modules is simpler from a circuit view point and efficient in all working conditions.

The connection in parallel combines the complementary characteristics of the system:

- batteries with high specific energy
- Sepercap's with high specific power

The characteristics of the mixed storage system allow the use Pb (sealed) batteries, that are more economic than NiMH and easily recyclable than the NiCd ones.

Special provisions are necessary for the parallel solution:

- Selection of the battery adequate size
- Precaution for placing in parallel.

Hereafter a simulation carried out on the same vehicle is reported.

It is possible to note the following zones:

- Starting at constant traction effort F (4 sec)
- Starting at constant power P (16 sec)
- Speed holding (50 Km/h)
- Braking with partial energy recovery (110A)

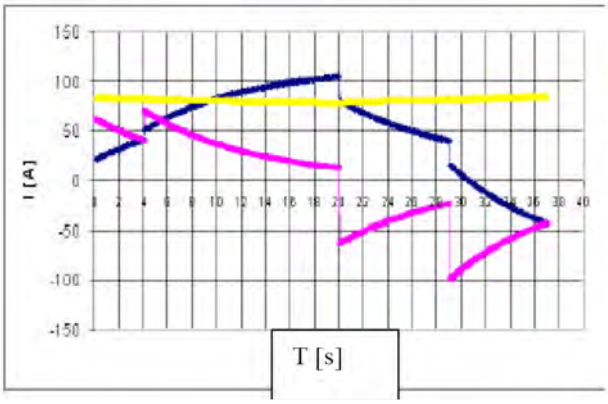

Fig. 7. Supercap's current (magenta line), batteries current (blue line), voltage in V (yellow line) for the mixed system

The efficiency of the Ultracap's action depends on the battery characteristic.

Batteries with reduced capacity (20 – 30 Ah) allow a prolonged operation.

In the specific case, the Ultracap's energetic contribution is 22 Wh (starting + braking), against 42 Wh of a battery (it represents about 50%)

V. NEW DEVELOPMENT

It's possible to use the same system also for urban applications :TRAM or trolley buses.

In both applications the supercap's modules allow the on board energy storage during the brake operations.

It's possible also to use this separate energy source to move the vehicle on the road in the dangerous situations (to exit outside the tunnel when the catenary is broken etc..).

This application allows short movements (depending on the energy stored : 100-300 m), but sufficient to recovery the vehicle and the passengers in a safety area.

500 Wh stored in the supercap's are estimated sufficient to allow this important function.

TABLE I I
ENERGY STORAGE SYSTEMS COMPARISON

	Specific Energy [Wh/kg]	Specific Power [W/kg]	Life cycle	Cost [Euro/Ke]
			Ke* [cycle•kWh/kg]	
Pb Batteries	35-50	100-150	500-1000	1.7
			30	
Ni-Cd Batteries	40-60	[illegible]	800	3.9
			40	
Ni-Mh Batteries	70-95	200-350	750-1200	4.1
			80	
Ni-Fe Batteries	50-60	80-150	1500-2000	3.3
			95	
Ultracap	1-1.5	200-2000	500000	5.9
			875	
Flywheel	6	300-500	350000	20
			2100	
Batteries + Ultracap	30	200		

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Increasing energy efficiency

Optimized traction power supply in mass transit systems

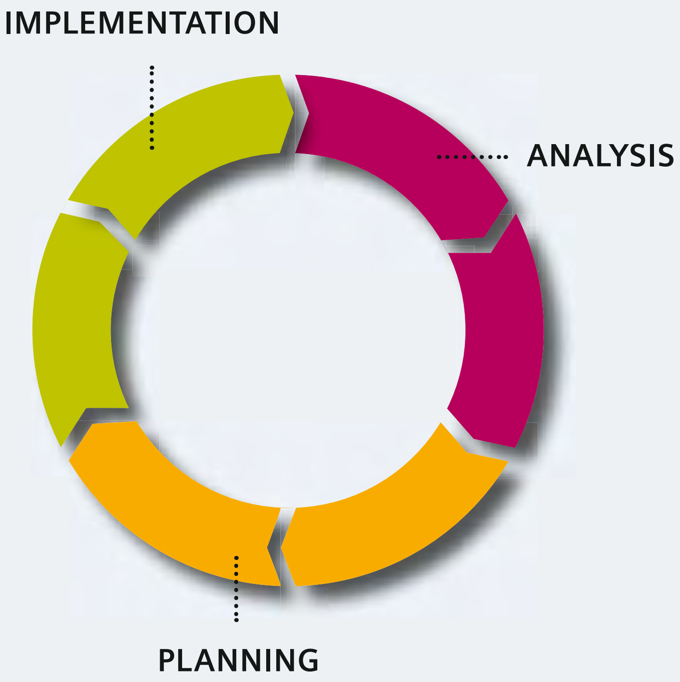
From virtuality to reality

Electrification solutions that pay

Safeguarding mobility is one of the big challenges facing our society today. To ensure our mobility in future, we need networked transport and information systems. But we will only be able to meet these mobility requirements through efficient coordination and perfect meshing of all modes of transport.

This is why Siemens – with its "Complete mobility" approach – is offering integrated transport and logistics solutions for safe, cost-effective and environment-friendly passenger and freight services. For Siemens has the necessary competence to provide everything from infrastructure systems for railways and roadways to solutions for rolling stock, airport logistics and postal automation.

Key elements of "Complete mobility" are efficient solutions for rail-based transport systems for cities and population centres and for connecting large cities and countries.



A HOLISTIC ELECTRIFICATION PROCESS

Thanks to our defined and holistic process, we ensure transparency and clarity in each phase of a project. In three steps, we help you to analyze your needs, plan your individual configuration and then concretely implement your tailor-made electrification solution.

Virtuality | 1

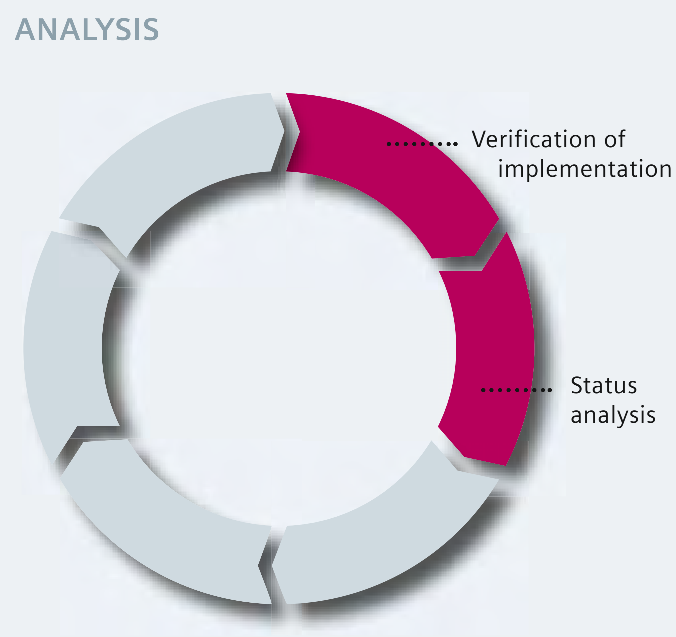
Siemens is one of world's leading suppliers of innovative railway electrification systems. The design and calculation of installations are among our core areas of competence. System know-how and the latest IT tools enable us to achieve a precise definition of your particular needs.

Profitable analyses

It's good that we're so calculating. After all, the complex requirements involved in the creation of an economically efficient and stable electrification system call for an in-depth analysis. Our experts work with the latest software modules and apply the experience they have gained from decades devoted to the development of such solutions worldwide.

Providing advice and finance:
A good starting basis for growth

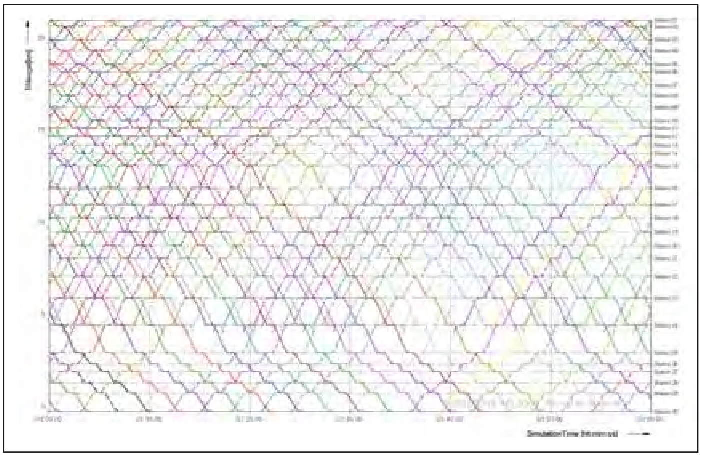
Our highly competent engineers and partners provide you with advice on all aspects of planning and system configuration from the very beginning. With our global network of innovation, we not only look beyond our own field of technology know-how but also have local needs closely examined by our worldwide network of on-the-spot experts. This enables a flexible variance analysis to be obtained on an international level. We consult with you closely to define the general parameters of the project right from the very first consulting session. To this end, we draw up an individual financing concept that is tailored to your situation and developed in close cooperation with local authorities, government offices and commercial banks all over the world.



Data acquisition:

The value added is in the details

Irrespective of the infrastructure, topography or climate, our experts collect your data straight from the actual source. In doing so, they are making use of data that is already available. However, it is frequently necessary to obtain new data as well in order to reliably evaluate the viability of a planned project. We carry out specific software-supported analyses, the results of which are incorporated as important parameters in the project simulation.



First planning unit:

Laying the foundations for decisions

With our Sitras® Sidytrac software tool, our experts generate crucial advantages that work out to your benefit. In an early phase of cooperation, you decide on the quality of the solution and the continuation of the project. On the basis of the acquired data, we draw up an initial project outline that allows alternatives at any time and thus creates a solid basis for a concrete offer to be made to you.

The result:

The right solution for the job in hand

Our extensive system know-how is based on the latest results from research and development by the relevant sections within Siemens as well as on our ability to draw the right conclusions from the calculations performed by our IT tools. These factors combine to ensure an optimal result ideally suited to satisfy your requirements.

Sample calculation: Payback period

The energy saved with Sitras TCI can give a return on investment in just three years.

Virtuality | 2

Efficient railway electrification systems are the result of exact planning. Long before work is started on site, we simulate your individual project under realistic conditions on the computer. This saves you from any surprises and allows us to take all contingencies into consideration.

Planning is knowing what the result will be

We always consider a project from a holistic point of view. Our experts plan your traction power supply system embedded in a larger context. On the basis of the data obtained and taking into account your special needs, we incorporate the relevant infrastructural parameters into the simulation of your system from the very beginning. As regards energy efficiency, the potential for savings can thus be determined as early as the first stages of calculation. This ensures a configuration that is both individual and easy on resources.

Sitras Sidytrac:
A little less, if you please?

Sitras Sidytrac is a simulation software that enables us to carry out an exact power-system calculation with train operation simulation for your particular project. In addition, workflows are standardized and automated, which means sources of error can be reduced and efficiency increased considerably. And that is regardless of whether you need a completely new system concept or simply want to know your existing system's potential for improvement. The software calculates your individual configuration and even goes a step further: due to the optimization of power consumption, power recovery behaviour and energy-saving potential, your resulting traction power supply system is not only exemplary in terms of ecology but also offers the beneficial side effect of substantially reduced lifecycle costs.

The following additional aspects of your system can be simulated and planned with Sitras Sidytrac:

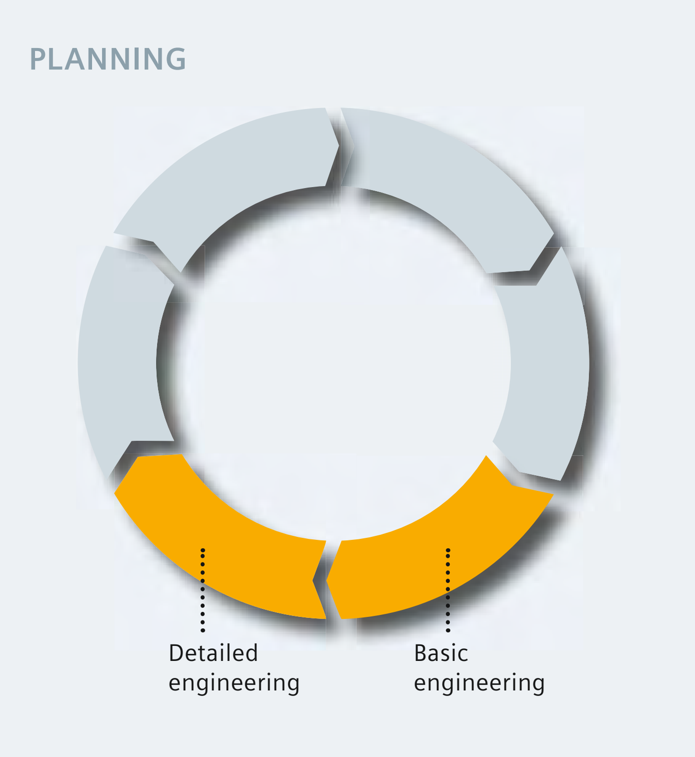
- The electromagnetic compatibility of your planned installation or the parts of the installation to be upgraded.
- An earthing concept that guarantees optimum protection for people and electrical equipment.
- The network reaction and voltage quality based on the analysis of
  - system interactions due to harmonics
  - three-phase imbalance because of single-phase railway loads
  - voltage fluctuations and flicker
  - resonance behaviour of line sections under realistic operating conditions.

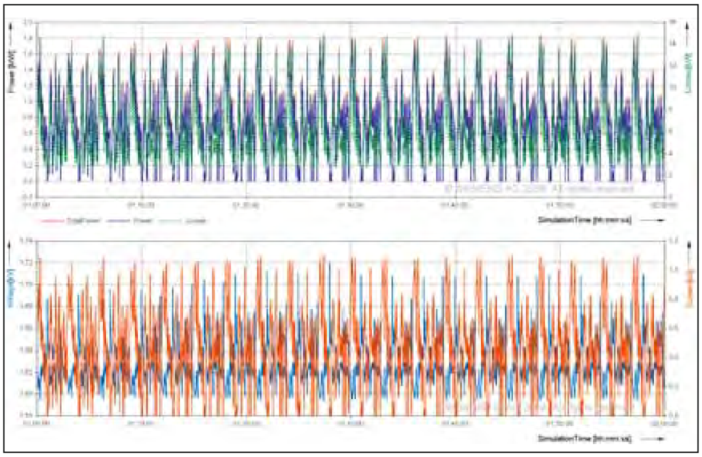
Concrete planning procedure:
Energy efficiency in three steps

Sitras Sidytrac wins over customers with its three-part program structure composed of input block, calculation block and output block. The input block is used to process the line data, the timetable, the vehicle data and the data of the electrical power supply system.

The calculation block is the heart of Sitras Sidytrac. First of all, the speed profile program calculates the location of the vehicles in the power supply network as well as the power they consume and deliver. These electrical loads are then incorporated in the static network and provide the basis for calculation of the dynamic electrical network. Then, the system determines the electrical load flow and incorporates the values in the speed profile.

The electrical data for the detailed design of the main components are finally evaluated in the output block. The results can then be shown in the form of predefined lists and graphics and stored in a database.





Planning example:
Energy storage units tap saving potential

The storage of braking energy by stationary energy storage units enables the primary energy demand of a rail vehicle to be reduced by as much as 30%.

Reality 1

The energy efficiency of railway electrification is mainly measured in terms of its energy saving potential. Siemens possesses a path-breaking range of products with the latest technologies for high environment-compatibility and greater economic efficiency. Once integrated in your system, our products enrich the ecological attribute of your electrification solution.

Efficiency you can grasp

With braking energy into the future? Modern technologies in the area of traction engineering considerably improve the drive system of rail vehicles and thus reduce energy consumption enormously. The energy storage units of the Sitras family are the heart of your custom-made electrification system. They save energy in daily use by storing the braking energy that is released and thus make a decisive contribution to the reduction of lifecycle costs as well.

Energy-efficient systems:
Three products for tailor-made solutions

Siemens can offer you three components that ensure the energy efficiency of your system in different ways. When performing the preparatory calculations, our engineers consult with you to determine the best possible energy storage product for your individual mass transit system.

Sitras TCI inverter:
More current for stops along the line

The Sitras TCI inverter makes it possible to transfer the braking energy into the higher-level medium-voltage power system. Large distances can be overcome easily so that even very remote consumers can be supplied with the necessary power. Since the medium-voltage power system is capable of absorbing the recovered brake energy at any time, the design of the braking resistors on the vehicles is also optimized – which means weight savings. Substations can also be retrofitted with a standby Sitras TCI inverter to make them capable of handling recovered energy. The robust and reliable thyristor technology ensures optimal energy transmission. Moreover, parameterization, control and diagnosis can be carried out by means of a standardized communication interface independent of the location.

Sitras SES based on Sitras ESM 125:
Energy saving potential you can rely on

The Sitras SES stationary energy storage unit creates optimum preconditions for energy recovery in mass transit systems. The Sitras SES can store and emit energy extremely quickly, enabling an exchange of energy with the vehicles. Besides that, the primary energy requirement is reduced by up to 30% without any influence on transport capacity or punctuality.

The core of Sitras SES: the new, compact Sitras ESM 125 energy storage module. The module's additional enclosure corresponds to a degree of protection of IP65 and contains additional fillers to provide extra operational safety. Tested by TÜV Süd according to BOStrab.

Sitras SES works in two modes:

- Energy saving mode: braking energy is absorbed, stored and later released for acceleration purposes.
- Voltage stabilization mode: the degree of charging is kept constantly high and energy is only released when the system voltage falls below a predefined limit.

Sitras MES/HES based on Sitras ESM 125:
Saving energy simply by driving

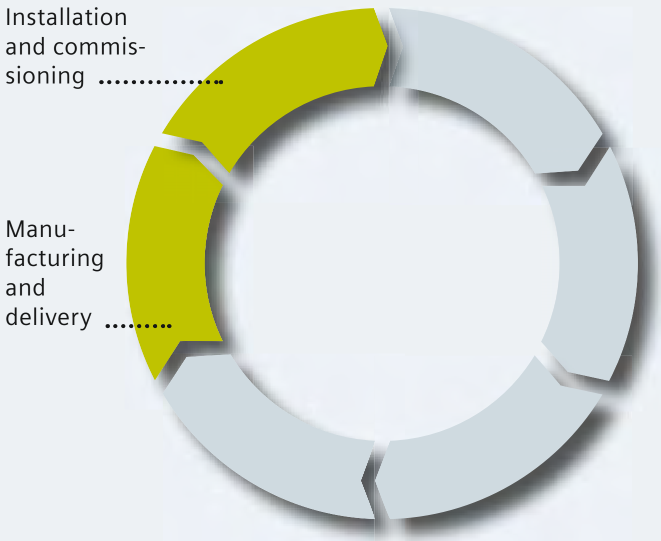
The Sitras MES and Sitras HES mobile energy storage units add a mobility factor to the proven technology of braking energy recovery. Electric and diesel-electric vehicles can be retrofitted with the systems.

The Sitras HES hybrid concept even goes one step further by combining the advantages of storage technology with the possibilities of a traction battery. Mass transit systems without an overhead contact line are thus possible and not only reduce energy costs, energy consumption and CO_2 emissions but can also be integrated into every urban environment almost without being noticed. These new variants also include the new Sitras ESM 125 energy storage module.

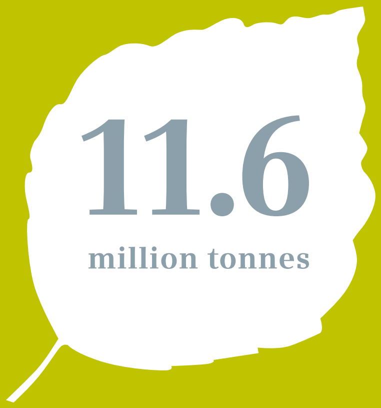
Continuous optimization:
Lifecycle under the microscope

Our work is by no means over when your mass transit project has been implemented. After commissioning, we continue to provide support for your system, subjecting the measured data and configurations to ongoing checks. Rationally based improvements can therefore be carried out at any time, assuring you that your mass transit system is operating efficiently.

IMPLEMENTATION



Saving energy globally: If all the DC railway systems in the world used energy storage systems or inverters, CO_2 emissions could theoretically be reduced by as much as 11.6 million tonnes.



This figure roughly corresponds to the CO_2 emissions of a central European city with one million people.

Reality | 2

In use worldwide

The energy efficiency of railway electrification is mainly measured in terms of its energy saving potential. Siemens possesses a path-breaking range of products with the latest technologies for high environment-compatibility and greater economic efficiency. Once integrated in your system, our products enrich the ecological attribute of your electrification solution.

Kölner Verkehrs-Betriebe AG
Cologne, Germany

From April 2001 to January 2003, Kölner Verkehrs-Betriebe tested a prototype of a Sitras SES stationary energy storage unit with double-layer capacitor technology. The result convinced the customer's experts. Only one year later, four energy storage systems were purchased and put into operation.

Scope of services: Four turnkey systems, including engineering, manufacture, installation and commissioning

Commissioned: 2003, 2004, 2006

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 750 V

Modes: Energy saving, voltage stabilization

Metro de Madrid SA
Madrid, Spain

In Madrid, two Sitras SES stationary energy storage units with double-layer capacitor technology ensure stable voltage conditions along railway routes. Simultaneous acceleration of several trains at a time is no longer a problem in the Spanish capital.

Scope of services: Two turnkey systems, including engineering, manufacture, installation and commissioning

Commissioned: 2003

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 750 V

Mode: Voltage stabilization

Beijing Metro
Beijing, China

Beijing, the host city of the Olympics, has been using the energy saving power and stabilizing capacity of four Sitras SES stationary energy storage units since February 2007. The stationary energy storage units are being used at a total of four installations.

Scope of services: Four turnkey systems, including engineering, manufacture, installation and commissioning

Commissioned: 2007

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 750 V

Mode: Energy saving

VAG Verkehrs-Aktiengesellschaft
Nuremberg/Fürth, Germany

Since 2007 VAG in Nuremberg has been able to rely on the energy saving potential and stabilizing capability of Sitras SES stationary energy storage units.

Scope of services: Four turnkey systems including engineering, manufacture, installation and commissioning

Commissioned: 2007, 2011

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 750 V

Mode: Energy saving

RET
Rotterdam, Netherlands

Since 2010, a Sitras SES stationary energy storage unit has been making sure that braking energy is absorbed, stored and released for acceleration purposes.

Scope of services: Turnkey system including engineering, manufacture, installation and commissioning

Commissioned: 2010

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 600 V

Mode: Energy saving

Toronto Transit Commission
Toronto, Canada

The Toronto Transit Commission has placed its trust in a Sitras SES stationary energy storage unit to reduce the primary energy demand of its vehicles and increase the reliability of its system.

Scope of services: Turnkey system including engineering, manufacture, installation and commissioning

Commissioned: 2011

Main components: Double-layer capacitor bank, converter, control system, connection unit

Supply voltage: 600 V

Mode: Energy saving

Bayerische Zugspitzbahn Bergbahn AG

Zugspitze, Germany

The installed Sitras TCI inverter has transformed the braking applications for vehicles operating on Germany's highest mountain. Part of the braking energy created by vehicles travelling downhill used to be dissipated at the brake resistor but can now be fed into the customer's own medium-voltage ring.

Scope of services: Turnkey system, including engineering, manufacture, installation and commissioning

Commissioned: 2007

Main components: B6 thyristor bridge, autotransformer, control electronics

Supply voltage: 1,500 V

Mode: Energy recovery for optimized power distribution

Metro Transportes do Sul S.A. (MTS)

Lisbon, Portugal

This hybrid energy storage system has been in operation for passenger services since 2008. And it has proved a great success – the vehicle is able to run without an overhead contact line on gradients of up to 2.6% and saves energy.

Scope of services: Engineering, manufacture, installation and commissioning

Commissioned: 2008

Main components: Hybrid energy storage system – consisting of a mobile energy storage unit and traction battery

Supply voltage: 750 V

Mode: Operation without overhead contact line

Innsbrucker Verkehrsbetriebe und Stubaitalbahn GmbH

Innsbruck, Austria

Innsbrucker Verkehrsbetriebe has been benefitting from the energy saving potential provided by a mobile energy storage unit since 2011.

Scope of services: Vehicle retrofitting: energy storage unit, modification of vehicle converter and control system

Commissioned: 2011

Main components: Mobile energy storage unit, vehicle converter

Supply voltage: 600 V

Mode: Energy saving

Siemens AG
Industry Sector
Mobility Division
Mozartstrasse 33b
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Germany

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Mass transit solutions for operation without overhead contact line.

Sustainable. Energy-efficient. Trendsetting.

Answers for infrastructure and cities.

Demographics. The composition of the world's population is undergoing a process of change. It is particularly in industrial states that the ratio between generations is becoming imbalanced. The population is on the increase and aging – and there is a rising need for innovative mobility solutions.

Sustainable.
Mobility with a vision.

Climate change. Worldwide CO_2 emission levels have to be reduced. The transport sector in particular features enormous potential for cutting down on CO_2 emission. Solutions are to be found in a detail-focused approach – and in the use of future-proof technologies.

Urbanization. Megacities are growing, almost unlimitedly. Today, more than half the world's population lives in cities. Against this background, it is a question of harmonizing individual mobility and energy savings – a challenge for mass transit in particular.

Focus on the city. More than ever before, the quality of life and competitiveness depend on cost-effective, future-oriented transportation systems. The requirements facing mass transit systems are increasing – especially in metropolises and conurbations. What is in demand is an optimum combination of speed, capacity, attractiveness and environmental compatibility. This is because cities need air to breathe. That is why new technologies should be capable of becoming easily integrated into existing infrastructures. It is only in this way that town planners, infrastructure decision-makers and mass transit operators can secure their investments sustainably.

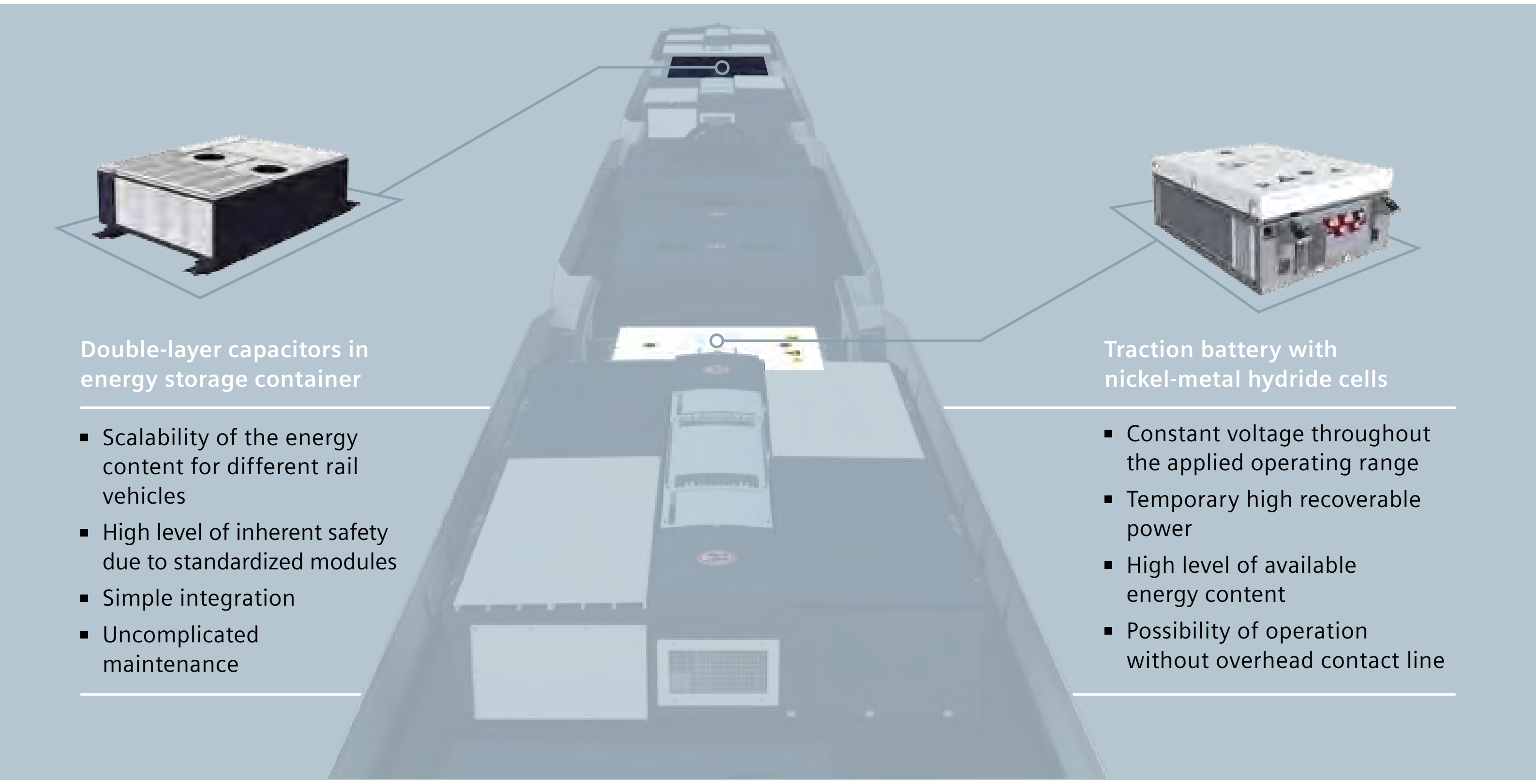
Energy-efficient.
Technology with potential.

Less energy consumption. Less CO_2 emission. More efficiency. These are the objectives of local authorities and cities. Objectives which can only be achieved by using innovative mobility technologies – sustainable technologies which Siemens is focusing on.

Complete mobility.
With more than 160 years of experience in passenger transportation, Siemens knows the requirements encountered in the urban environment and offers conurbations a full-scale portfolio of future-proof technologies. With this in mind, we are applying our "Complete mobility" approach to implement solutions for sustainable city and transportation development. Environmental and climate protection are considered just like aspects of cost-effectiveness and efficiency. One innovative example is the Sitras® HES hybrid energy storage system.

Cost-effective energy storage systems.
Sitras HES opens up entirely new perspectives for cities – thanks to its intelligent storage and usage of braking energy. Vehicles featuring this technology consume up to 30 % less energy per year and emit up to 80 tons of CO_2 less. What is more, the traction power supply becomes more stable since the voltage drop along the overhead contact line is reduced, particularly in high-peak operating periods. Sitras HES enables trams to run without overhead contact lines for distances of up to 2,500 m. Whether in tunnels, on bridges or at major intersections, the system is particularly suitable for complex structural locations which make it difficult to install overhead contact line. Moreover, routes without overhead contact line mean less installation work, and that, in turn, entails lower electrification costs for operators and more flexible possibilities for town planning. The special feature of our system is that it is designed to function on narrow-gauge railways too. A system which both cuts energy consumption and adds to the attractiveness of the cityscape.

Effective combination.
Sitras HES consists of two basic components: the Sitras MES mobile energy storage unit and a traction battery. In addition to storing braking energy, Sitras HES uses this storage function to provide a new operating mode – operation without overhead contact line. Control in this energy-efficient operating mode can be adjusted to such a precise degree that the optimum solution required by the customer can be achieved – energy savings and peak power reduction. If more energy is generated during braking than can be stored, this energy is fed back into the contact line. The hybrid concept can be integrated into new rolling stock and existing vehicles can be retrofitted with this system too. In this way, not only energy consumption, energy costs and CO_2 emission can be reduced, but the cityscape can also be visibly preserved and enhanced.

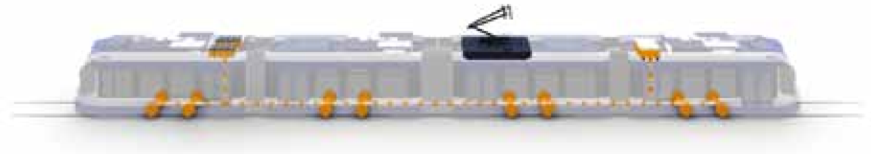


Double-layer capacitors in energy storage container

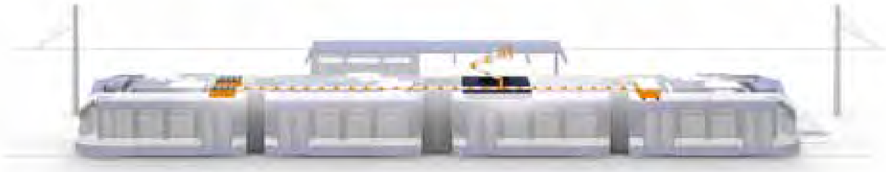
- Scalability of the energy content for different rail vehicles
- High level of inherent safety due to standardized modules
- Simple integration
- Uncomplicated maintenance

Traction battery with nickel-metal hydride cells

- Constant voltage throughout the applied operating range
- Temporary high recoverable power
- High level of available energy content
- Possibility of operation without overhead contact line



Charging of the energy storage system by braking during operation



Charging of the energy storage system on routes with overhead contact line and at charging stations or stops within just a few seconds by local charging units at stations or stops

Trendsetting.
Performance with a future.

Storage system for usage of braking energy. Worldwide CO_2 savings of up to 4.6 million tons. So that both human beings and the climate can breathe. Modular retrofitting and platform concepts ensure that these perspectives become reality.

Convincing hybrid concept.
Energy storage systems are future-proof – for both the climate and the operators. Siemens has therefore developed a retrofitting option which enables the energy storage unit to be subsequently connected outside the traction converter too. The Sitras MES and Sitras HES energy storage systems are optional components of Siemens' new Avenio tram platform. An efficient overall solution which has already proved itself in practice. In Portugal, south of Lisbon, Siemens' Sitras HES hybrid energy storage system has been in passenger operation since 2008. With success too, since the trams run without overhead contact line on gradients of up to 2.6 % and save energy. Environmentally friendly and cost-effective at the same time, this system proves how smoothly both operating modes function.

Overview of benefits.

Cost-effective and environmentally friendly

- Reduction in energy demand by up to 30 %
- Optimization of life cycle costs with 99.8 % availability
- Lower cost-intensive peak power demand
- Larger intervals between stops and substations
- Reduction in CO_2 emission by up to 80 tons per vehicle per year

Powerful and safe

- Increase of performance by reducing the voltage drop within the traction power supply
- Scalable energy content
- Simple retrofittability
- Equipment for Avenio
- Tested by TÜV Süd (German Technical Supervisory Association) in line with BOStrab (German Construction and Operating Code for Light Rail)

Future perspectives. Whether on roads, on rail or in the air – in future, transportation has to be controlled and networked even more intelligently. It is only in this way that the existing infrastructure can be used efficiently and, at the same time, our climate protected. With this in mind, Siemens offers a wide range of possibilities – and is continuously developing new systems, products and technologies which set new criteria in terms of climate neutrality. Thanks to their scalable energy content, our energy storage systems can be used not only for trams but also in other rolling stock. We benefit from our many years of experience and our technological know-how. What is the reason for our strength? We offer not only mobility solutions from a single source but also an incomparably full-scale portfolio.

Put your future on the right tracks and contact us!

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Siemens AG
Infrastructure & Cities Sector
Smart Grid Division
Humboldtstrasse 59
90459 Nuremberg, Germany

Siemens AG
Infrastructure & Cities Sector
Smart Grid Division
Rail Electrification
Mozartstrasse 33 b
91052 Erlangen, Germany

electrification.mobility@siemens.com
www.siemens.com/rail-electrification

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Edinburgh Tram Network

Wire-Free Traction System Technology Review

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Parsons Brinckerhoff Ltd
Edinburgh Tram Network
SDS Provider
16 Abercromby Place
Edinburgh, EH3 6LB

Telephone: 44(0) 131 272 3318
Facsimile: 44(0) 131 272 3302
Email: edinburghtram@pbworld.com

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AUTHORISATION PAGE

Title: Non-Functional Requirements Specification				
Approvals	**Name**	**Position**	**Signed**	**Date**
Author	J Baggs	Technical Director		
Reviewer	C Mason	Design Manager		
Project Manager	P McCauley	Project Manager		

Description

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2	17 Jan 06	Internal and External Comments	Reviewer	PB
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EXECUTIVE SUMMARY

As part of a series of technology reviews required to be carried out under the SDS contract for the Edinburgh Tram Network, Parsons Brinckerhoff (PB) have conducted an investigation into the options for a wire-free traction system, in order to see if there is a viable alternative to the use of a conventional overhead power supply system either throughout the system or just within the World Heritage Site. The need to look carefully at this subject arises from the aspiration to avoid the use of overhead equipment particularly in the most visually sensitive areas if possible. A survey and assessment of the full range of available options has been undertaken, in light of the specific operational requirements of the Edinburgh Tram Network and the provision required for the future construction of Line 3, with a view to seeing whether it will be possible to provide a wire-free system by using any of the means currently available.

To provide a complete and robust review of the possibilities the available options have been examined and evaluated using a series of standard criteria, namely: weight, re-fuelling, noise and vibration, vehicle life, vehicle availability and reliability, vehicle compatibility with infrastructure, passenger capacity impact, performance and capital and operating cost. The options fall basically into two groups:

- *On-tram solutions* - Involving generating and/or storing traction energy on the trams to allow them to operate independently of an overhead supply.
- *Infrastructure solutions* - Supplying power to the tram from the infrastructure but without the use of an overhead supply.

The on-tram solutions examined were traction batteries, flywheels, fuel cells and super capacitors, together with an on-board prime mover, with or without energy storage (diesel or diesel hybrid). In the case of the on-board prime movers, alternative fuels such as liquid petroleum gas were not pursued in detail, as they are merely variations on the same basic theme.

Within the infrastructure solutions the number of available options is much lower and the review therefore considered only two main alternatives: the French APS or ‘ground power’ conductor rail system as used in Bordeaux, and a modern equivalent of cable haulage

Each of the options was considered in the context of its current state of development and availability to suit the timescale of the project. Its suitability either for the operation of the central part of the Edinburgh network or for the complete network was also a major factor. Capital and operating costs were considered mainly in comparative terms since detailed data is not generally available for the novel solutions concerned.

The modern low-floor tram is a well-developed product that is available from a limited number of major international suppliers. The Edinburgh system for which Bills have been deposited in the Scottish Parliament is based around the use of technology of this general type. The technology review therefore took standard low-floor tram technology as a starting point in examining the options for powering it.

None of the developed or potentially available on-vehicle energy storage systems would have the operating range and endurance to meet the requirement for wire-free operation within the World Heritage Site, although all of them would permit some movement over relatively short distances and with varying operational restrictions.

Each of the options would add significantly to the cost and weight of the vehicle. In the case of the battery option the passenger payload would have to be reduced to compensate, as it might to a lesser extent for the other options.

Super capacitors have been developed primarily to improve energy efficiency and might be worth pursuing for that reason alone, although they could also provide some very limited wire-free capability.

The wholly diesel-powered option which would involve adding a prime mover to the tram is incompatible with the basic system concept, in terms of its performance, availability, reliability and other factors.

The hybrid diesel-electric option, capable of operating from an overhead supply outside the city centre and from the engine or from batteries charged by the engine within the World Heritage Site, would offer greater operational flexibility but would not meet the system performance requirements when away from the overhead. There would be an increase in vehicle cost and weight, combined with a reduction in passenger payload of about 10% or more and a reduction of approximately 50% in tram performance.

The French APS ground power system is free from the limitations of distance and range associated with most of the alternatives and it also avoids some of the weight associated with the on-tram alternatives. However, it does impose certain operational restrictions, primarily in terms of maximum speed.

APS has not yet achieved an acceptable level of reliability on a network wide basis, although the indications are that it may do so in the future. The greatest difficulties involved with its possible use in Edinburgh relate to the fact that it has only been applied in one city so far, Bordeaux, under climatic and regulatory conditions that are very different from those applying in the UK. It is most unlikely to be available within the required timescale, if at all. Further factors which operate against it are the difficulty that the power system and the trams that run on it would only be available from a single supplier, which would rule out effective competition in this key area, and the significant visual impact of the power supply rail on the road surface and paving.

Cable haulage although widely used for specific applications such as segregated airport shuttles would not meet the operational requirements of a modern urban tramway and would be expensive to implement and maintain. The regulatory and approvals issues that it would raise would be considerable and again it could not be available within the required timescale even if the basic objections to it could be overcome.

Of the options considered only the APS system comes close to having a network-wide capability. Its introduction in Edinburgh would, however, raise many issues including legal and regulatory ones. These problems would be more severe because at the present time it is used in only one other city, has still to achieve the necessary level of reliability and has not been subjected to the anything like the climatic conditions found in Edinburgh.

None of the on-vehicle options comes close to meeting the operational requirements within the World Heritage Site although the use of super capacitors would probably be worth considering for reasons primarily of energy efficiency. This approach might enable some limited wire-free operation, for example through little used emergency crossovers, but this would essentially be a bonus rather than the main reason for adopting it.

In conclusion, at the present time there does not appear to be a feasible alternative to the system-wide use of an overhead contact system without importing a significant degree of risk. For that reason work should proceed on the basis that the whole of the system should be wired, at least initially. In parallel with that, the tram procurement process can take into account the possible wider benefits from the use of super capacitors and test the market to see what is on offer at the time, at what price and with what guaranteed level of performance. It might then prove possible, for example to leave certain emergency crossovers unwired and to use the energy storage system when operating through them.

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1 BACKGROUND

1.1 Purpose of the Project Management Plan

PB Limited is required to carry out a review of a number of areas of technology at an early stage as an essential part of the responsibility for the development of the system design under the SDS contract. A number of subjects for Technology Review were identified in the SDS scope of services, Section 2.5. In addition the need to examine alternative technologies such as wire-free current collection for traction purposes were identified elsewhere in the brief e.g. 2.4.2.3.

This Technology Review is concerned with the implications of a possible wire-free current collection system. In this context ‘wire-free’ means a traction system that does not rely upon an overhead contact wire for all or part of the route.

New tram systems have been introduced in many countries in recent years. While some of those within the British Isles show clear evidence of a ‘learning curve’ so far as the design of overhead equipment is concerned, there are many international examples of systems that are both well designed and in sympathy with their surroundings. Closer to home the new tramway in Dublin is a good example of how well designed overhead can improve the quality of a system.

However, no matter how well designed any overhead system is, it will still be visible and will cause a degree of concern, particularly at the planning stage. The City of Edinburgh’s Draft Design Manual of July 2005, refers to the need for a wire-free traction system to be seriously examined as an alternative to a conventional overhead power supply. It refers in particular in Section 4.43 and elsewhere to the aspiration for a ‘wire-free’ power system and the reasons for this.

In addition, the promoter, City of Edinburgh Council, has received representations from a number of interest groups, particularly those concerned with heritage and environmental issues, on the desirability of avoiding the use of overhead line equipment within the World Heritage Site and more widely if at all possible.

This review addresses the issues raised in the Draft Design Manual and by the other interest groups. It examines the options to the use of conventional overhead equipment and considers the strengths and weaknesses of each and their suitability for use on the Edinburgh Tram Network, either solely in the most sensitive areas or more widely. Although it is assumed that any overhead equipment used on the Edinburgh network will be designed to the highest aesthetic standards, such considerations do not form part of this review which is confined to the consideration of the alternatives to such a system.

2 INTRODUCTION

Before evaluating the various options to the use of overhead equipment it is necessary to identify them and establish which of the options merit more detailed analysis. The Draft Design Manual identifies the need to consider the options to the use of an overhead contact system in the most visually sensitive parts of the system and possibly more widely.

It is clear that a number of options have been examined in the course of developing the project and prior to the involvement of PB. These are outlined in the Witness Statement of Scott McIntosh of Mott MacDonald of 31st May 2005 and the report by Roger Jones of **tie** to the Murrayfield Community Council of 3rd June 2005.

Both these reports examine a number of options and both, to some extent, also include a comparison of the alternatives with ‘best practice’ in respect of the design and installation of overhead power equipment.

This review focuses entirely on the potential options to an overhead power system and does not consider the design of the overhead system itself other than in respect of the possible interfaces between the two power supply systems at transfer points.

Two alternative approaches to the use of a wire-free system are considered. These are:

- For the whole of lines 1 and 2, and,
- Only for the length of route through the central part of the World Heritage Site (from Shandwick Place to Picardy Place, a distance of about 1.8 to 2.0km).

All the central section referred to above would be used by trams on both Line 1 and Line 2, while about 1.3km of it would also be shared with trams on Line 3. The eventual combined tram frequency on the common section could be up to about 24 trams per hour and per direction. There are four tramstops on the section of route within the World Heritage Site and the average distance between stops is therefore about 600 metres. The section of route is generally flat and straight or curves only gently apart from the route into and through St Andrew Square which has curves of approximately 25 metre radius on the tracks connecting to it in each direction and gradients of about 7 or 8%. This section is likely to be the most demanding for any system of wire-free traction.

The various options are assessed in terms of their implications and suitability for the two main requirements outlined above: either for the whole of the route or merely for the section within the World Heritage Site.

The principal features of each option are discussed and their characteristics established on a common basis. In order to make a comparative assessment the implications of each are reviewed under the following headings in accordance with the SDS Technology Review Scoping Report of November 2005:

- Functionality – the ability to deliver against the requirements specification
- Availability – both for the initial installation and ongoing operation
- Impacts – including construction and visual ones
- Safety
- Hazards
- Costs – both initially and on an ongoing basis
- Risk profile – in the first instance and subsequently

- Reliability, Availability, Maintainability and Safety

3 THE MAIN OPTIONS

The main alternatives to the use of an overhead power supply system fall into two main groups:

- **On-tram -** power sources that could be installed on a tram to enable it to operate independently of an overhead power supply, either for a limited time and distance (for example through the World Heritage Site) or on a continuous basis for the whole of a typical duty cycle.
- **Off-tram -** power sources, other than overhead, that are part of the infrastructure and independent of the tram. These must be capable of supplying power, or traction in some other form, to the tram either for a limited distance (for example through the World Heritage Site) or throughout the network.

Each of these categories has been examined in turn to identify systems that already make use of relevant wire-free technology which might be applicable to Edinburgh. It is apparent that the number of potentially viable options in each group is in fact quite limited for an intensive urban operation. Although there has been substantial growth in the number of tramway systems worldwide in the past few decades and significant extensions to many of the longer-established ones, nearly all of these use a conventional overhead power supply. A small but increasing number do use dual-voltage traction equipment to allow trams to inter-work over local electrified railway lines, but in only a few cases are power sources other than an overhead contact wire involved.

Although a great many different traction arrangements have probably been put forward for light rail systems at one time or another, we have concluded that the options should be reduced to the main generic types and that there would be little benefit in examining the more marginal ones or ideas that are merely variations on the main themes. On this basis the main options for wire-free traction have been identified as:

- **On-tram** power sources.
    - Batteries
    - Flywheels and traction capacitors
    - Fuel cells
    - Diesel either as the main or as an auxiliary power source (including alternative fuel sources such as LPG to achieve the same purpose)
- **Off-**tram infrastructure alternatives
    - Ground level surface contact (Alimentation par Sol - APS)
    - Cable traction (Soule or equivalent)

All other realistic alternatives should be covered to a greater or lesser extent by these options.

Each option has been analysed in turn on the basis of either published data, input from potential suppliers or a review of existing comparable systems. In each case we have considered its suitability for use on the Edinburgh Tram Network together with the type and level of risk that it would import to the scheme. None of the options is likely to be entirely risk free and the risks that have been considered include regulatory approvals, construction, cost, programme, operational performance and reliability factors. We have also considered whether the evaluation would differ if an option were considered for use throughout the network as opposed to only on the most sensitive parts of the route.

Unless they are to be used continuously throughout the tram network each of the options would impose some time delay during the changeover from one mode of operation to another and interlocks would have to be put in place to ensure that a tram could not, for example, move off with its pantograph raised or its shoe gear 'live' when it was in an alternative mode of current collection.

4 ON TRAM OPTIONS

4.1 Batteries

There have been considerable developments in the field of batteries for traction purposes in recent decades. These developments have had the effect of gradually improving the life and performance of the batteries, while at the same time improvements have been made to the control equipment and motors used with them. This has resulted in more economical packages with a greater operating range being available but it has not yet provided the major breakthrough that has been promised for several decades. At the present time batteries on their own are still some way from being able to meet anything like a typical urban transport duty cycle – particularly for a vehicle with the size, weight and passenger payload of a tram.

Batteries are by their nature bulky and of limited endurance. Thus most of the commercial applications are for vehicles which are required to operate only for limited periods with sufficient time in between periods of use for re-charging (such as at airports and for certain sorts of deliveries). In the passenger transport field traction batteries tend to be used mainly for vehicles like trolleybuses to enable them to manoeuvre for a limited time off the overhead wire. This is typically to deal with an emergency or to allow overhead equipment to be simplified in a depot. The batteries are re-charged when they are operating normally from the overhead.

This approach is rare on tram systems but the new Bordeaux system uses traction batteries to supplement the APS ground power system, to allow the tram to keep moving in the case of a local interruption in the supply, and the system under construction in Nice will use batteries on two relatively short sections which will not be equipped with overhead. The Caen hybrid 'guided trolleybus' system which has been in operation for some time also uses traction batteries but only when travelling out of service between the depot and the nearest part of the route.

A further variant is provided by some trolleybus systems on which the traction battery is re-charged by an auxiliary engine and generator when the bus is operating away from the overhead line. This enables the vehicle to operate independently without having to have a fully rated automotive engine to drive it and permits it to operate for a substantial period without the risk of it becoming stranded due to flat batteries, for example for a route extension. Hybrid vehicles of this type are in a distinct category and are considered in more detail in Section 4.5 below.

For rail vehicles that are to rely entirely or mainly on battery power the implications will vary depending on the approach which is employed. For an urban tramway such as Edinburgh the use of a vehicle whose batteries are only re-charged 'out of hours' or when it is standing at the terminus is precluded by the stop spacing, route length, gradient profile and duty cycle. This is because the demand on the battery when running over a route of this type would be such that an uneconomically large battery would be required and the time to re-charge it at the end of each journey would be excessive. Although the experimental battery railcar unit which operated between Aberdeen and Ballater some years ago, had its batteries recharged at the terminus in this way during a significant layover, this approach would not be suitable for an urban tramway.

A pure battery tram would not therefore be a feasible proposition and an overhead/battery powered tram would have to spend most of its time operating from the overhead and only rely on its battery for a limited period of time and part of the route.

The trams in Bordeaux which entered service about two years ago have traction batteries which enable them to operate independently of the infrastructure. However, they are only designed to use their batteries in the event of the failure of a short section of the APS ground power system.

The batteries for this very limited duty add about 0.85 tonnes (2%) to the weight of the tram. We understand that they are currently being replaced after two years service but this may be untypical because of the teething problems with the APS system.

The Nice trams, which will have to operate over two sections each of just under 0.5km at a speed of about 40km/h, and carry about an extra 3 tonnes of batteries and associated equipment (about 8.5%) to power them. They will use Saft NiMH (Nickel-metal hydride) batteries and will incorporate a battery cooling system. At the present time the Nice trams have still to enter service so there is no experience of their performance.

While a reduction in speed should reduce the demand on the battery and increase the range of the vehicle, anything other than straight level track would have the opposite effect. It is interesting that in the case of the Nice tram, even with a relatively large traction battery and the advanced technology being used, the length of time that the car is able to operate away from the overhead line, will be strictly limited.

Both Bordeaux and Nice either use or will use the Alstom Citadis tram so they may be considered to be representative of the performance and battery requirements for other similar trams in current production.

The only practical approach for a battery/overhead tram would be to use the battery only for a very limited period, for example to travel through a part of the World Heritage Site, and to operate from an overhead supply for the rest of the time. It appears that the duty cycle in Edinburgh will be approximately four times as demanding as that in Nice before local factors such as the gradients on South St David Street and South St Andrew Street are taken into account. Even a battery of the size proposed for Nice together with a significant limitation on the maximum speed of the tram would therefore only enable a tram to operate in wire-free mode for about a quarter of the distance within the World Heritage Site. There must be some doubt as to whether it would be possible to deliver a practical solution within the constraints of a relatively standard tram, even before issues such as cost and reliability are taken into account.

Taking each of the main factors into account our assessment of this option is as follows:

Weight: The batteries would add about 3 tonnes to the weight of the tram; significantly more if the desire to operate in wire-free mode through the World Heritage Site was to be met. This would be likely to mean that the passenger payload must be reduced to compensate. The cost of having to carry this additional weight around at all times would also have to be taken into account.

Re-fuelling: The combined battery/overhead vehicle would not require re-fuelling, though close attention would have to be paid to the need for frequent re-charging.

Noise and vibration: The battery/overhead vehicle should be no noisier nor vibrate any more than an equivalent conventional overhead electric vehicle.

Vehicle life: The life of a battery/overhead vehicle would not differ significantly from that of a conventional electric vehicle, the batteries would however have a limited life and would have to be replaced on a regular basis.

Vehicle availability and reliability: A battery tram would not have the same high level of availability and reliability as a conventional tram. The additional maintenance tasks and the time required to carry them out would impact on vehicle downtime and it must be assumed that battery and charger problems would arise from time to time either when the cars were in service or being prepared in the depot. With sufficient experience the effect of ageing on the batteries could be offset by replacing them after a shorter life although this would involve spending the equivalent of about 5% of the capital value to the tram every few years. A further factor is that the constant replacement of the traction batteries is not without its own environmental cost. While the details of this would depend upon the type of battery finally chosen, it is likely that the relatively sophisticated substances involved in its manufacture could be difficult to dispose of.

Vehicle compatibility with infrastructure: A vehicle which made occasional local use of batteries would be broadly compatible with the system infrastructure. Substantial facilities would however have to be provided at the depot for charging, handling maintaining and storing a large number of bulky and heavy batteries.

Passenger capacity: The capacity of a tram equipped to operate for a strictly limited period from a battery would probably be about the same as for a conventional tram, subject to an analysis of such issues as weight distribution and axle loading. A battery/overhead tram able to operate through the World Heritage Site would almost certainly have to sacrifice some part of its passenger payload to remain within acceptable limits on the track, body structure and trucks.

Performance: Vehicle performance will be limited by the capacity of the battery. The most advanced vehicle currently in build, which has still to enter service, appears to have about a quarter of the range that would be required to cover the World Heritage Site in Edinburgh and will be subject to a reduced top speed when in battery mode. Any steps to increase range or performance by measures such as providing charging points at tram stops to top up the battery would introduce significant additional complication and would be likely to adversely affect overall system performance.

Capital and operating costs: The capital and operating costs for an overhead/battery tram would be significantly greater than for a conventional one. The costs would include the higher cost of more complex and non-standard trams together with the additional fixed equipment at the depot, additional spares, handling costs and the regular replacement of the batteries. Reduced vehicle reliability and availability might also necessitate the provision of a marginally larger fleet.

Summary: While at first sight batteries might appear to be an option for a wire-free traction system within the historic city centre of Edinburgh, closer examination indicates that they would not be able to power the section of route within the World Heritage Site, let alone the complete system. A new system that will use traction batteries to a more limited extent will go into public service in the next year or two but its performance and longer term implications are at present unknown. There is no tramway vehicle either in service or under development which meets the operational need within the World Heritage Site.

Adopting traction batteries for any significant part of the route would add substantially to the capital cost of the tramway and introduce significant additional operational performance and reliability risks. Even a limited application would raise the same issues and have a negative effect on ongoing operational and financial performance of the system.

4.2 Flywheels

Flywheels have been used to a limited extent for some years. They were used on a commercial scale in Belgium to power urban buses until about 40 years ago. In that application the electrically powered flywheel was charged by means of static charging points located at bus stops. The aim was to obtain trolleybus performance but without having to provide extensive and unsightly twin-wire overhead equipment. The flywheel units were large, expensive and not very efficient; apparently one of the reasons why the services were discontinued was because the flywheel became discharged during delays in road traffic. In recent times the same principle has been applied in a simpler form to the ‘Parry People Mover’ system.

Much lighter, smaller and more sophisticated flywheels have since been developed based on high speed centrifuge technology, initially by companies such as Urenco. These have been applied in a static form in traction substations to increase overall energy efficiency by storing regenerated energy produced during the braking of electric trains.

More recently the technology has been applied on vehicle as well as to substations and during 2005 Alstom have carried out trials on the Rotterdam tram system with a Citadis tram equipped with a roof-mounted high-speed flywheel pack. The use of composite materials has enabled the speed of the flywheel to be increased to between 10,000 and 20,000 rpm and the size and weight to be correspondingly reduced. During recent trials a tram was operated across the Erasmus bridge in Rotterdam for a distance of about 900 metres with an AW3 loading (5 passengers/m^2) solely by means of its flywheel pack.

The real purpose of the flywheel development however, as with traction capacitors which are also considered in this section, is to achieve significant improvements in energy efficiency rather than to secure local independence of the overhead. The flywheel permits re-generated energy which cannot be returned to the overhead line because there are no trams available to take advantage of it, to be stored until either the tram that has produced it or another tram is able to make use of it. This enables the proportion of braking energy which is re-used, rather than turned into heat, to be increased significantly.

The work that has been carried out recently by Alstom has been in the nature of a “proof of concept” process and they have still to decide whether to pursue the development of the unit and offer it commercially. There is little doubt that from an energy efficiency point of view the trial has been successful but it is likely that further trials will be carried out before a decision is made on whether to offer it as an option. The view of many in the industry is that energy storage using flywheels is a valuable concept but that it is better carried out at the substations than on the vehicles. At the present time there is very little detailed information available on vehicle flywheels because the product is not yet being pursued commercially.

Although the capital cost of the equipment is unknown, a flywheel equipped tram would clearly be more expensive to buy than a conventional one, but the additional weight should be more than offset by the increased energy efficiency from the use of the flywheel. The unit life, operating and maintenance costs are unknown. Of these items it is medium and long-term maintenance which raises the most questions. The unit is required to operate at very high speeds and contains elements that are safety-critical. It can therefore be assumed that maintenance will have to be carried out off-site by a specialist firm on a unit exchange basis. The implications of this from a cost and availability point of view would require further investigation.

Flywheels on their own do not appear likely to provide the basis for a wire-free traction system either within the historic city centre or more widely. The general view seems to be that if flywheels have a future it will be as a means of increasing overall energy efficiency, rather than to provide independent movement away from an overhead supply. In that case there seems to be a strong argument for locating the flywheel at the substation rather than on the tram.

Weight: 1 tonne (subject to confirmation)

Re-fuelling: There would be no requirement for re-fuelling with flywheels.

Noise and vibration: A modern high speed flywheel should not produce any noticeable noise or vibration (subject to confirmation).

Vehicle life: The installation of a roof-mounted flywheel should not have any effect on the life of the vehicle. The economic life of the flywheel and its maintenance requirements are not known at present.

Vehicle availability and reliability: The provision of a flywheel is not likely to have any adverse effect on vehicle availability. Reliability should be unaffected while the consequences of any unreliability in service (such as through a temporary loss of power supplies or local damage to the overhead) could be reduced as a result of the greater operational flexibility provided by the flywheel.

Vehicle compatibility with infrastructure: The interface between the vehicle and the infrastructure should be largely unaffected except that the interface to the power supply system should be improved as result of the greater energy efficiency of the trams.

Passenger Capacity: The flywheel would have no adverse effect on the capacity of the tram from a space point of view but some passenger payload may have to be sacrificed due to the additional weight . It should have a positive effect on the capacity of the traction power system.

Performance: Flywheels should enhance the normal operation of the system by ensuring that the power system is more robust and that there is some additional operational flexibility due to the limited 'off line' capability. They would not have anything like the independent capability that would be required to provide a wire-free solution within the World Heritage Site.

Capital and operating cost: The capital cost of the trams would be increased by the addition of a flywheel pack as would their maintenance costs. It is not possible to quantify either of these items at the moment although they would probably be significant. If it became a commercially available item the first cost of a flywheel equipped tram would probably depend very much on the manufacturer's commitment to launching it at an attractive price and the likely volume of sales. The price for a small quantity for one system is likely to be unattractive.

Summary: Experience with the use of flywheels on trams is very limited. The need to improve energy efficiency is providing the main impetus to their development and application. At the present time it is not a commercially available item although a significant amount of testing has been done under operational conditions. The ability to operate off-line for a limited period appears to be more of an incidental by-product of the basic development than a primary objective. It is not clear whether all the safety issues associated with installing a high speed unit on the roof of a tram have been satisfactorily addressed.

4.3 Super Capacitors

A traction capacitor is a device which is used to store energy on the tram, typically when braking or when another tram is braking, and then use it to reduce the demand on the power supply system when the tram needs to accelerate. Until recently such devices have been far too heavy and too expensive to be either economically viable or practical for installation on a tram. The steady development of better and cheaper products in the field of power electronics has enabled more suitable capacitors to be produced as was the case some years ago with traction control equipment.

In recent years Bombardier have developed the MITRAC double-layer capacitor unit. Since the middle of 2003 a unit has been on trial on a normal Bombardier service tram in Mannheim. The trial will continue for some time but the unit has already accumulated the equivalent of over a year's running on the most intensive type of urban tramway. The unit is fitted to the tram in normal service and is used to supply one of the two inverter units on the car. The other inverter is fed normally from the line. This arrangement makes it possible to directly compare the power consumption and energy efficiency of the two units, although for a future production application the intention would be to fit a capacitor in conjunction with each traction inverter.

As noted above the capacitor works by storing braking energy, either from the tram to which it is fitted or from other trams which would otherwise have to feed the regenerated energy into their braking resistors.

The analysis that Bombardier have carried out indicates that fitting a fleet of trams with capacitors should save of the order of a further 30% of traction energy on top of the 15% saving typically saved by regeneration. This apparently high figure arises as a result of a combination of eliminating the need to feed braking energy to the resistors and a reduction in the distribution losses due to the reduction in the proportion of power taken from the substations. The projected performance for such a system in Edinburgh could be analysed by means of a simulation.

The capacitor system is not designed primarily to provide an ‘off-line’ capability but it does have the ability as a matter of course. Unlike a flywheel the capacitor retains its charge for a substantial period. It gives the tram the ability to run for a limited distance without using the overhead, for example within the depot or through (unwired) crossovers or in the event of a local overhead line fault. The distance possible will depend on the state of charge of the unit at the time and other factors such as passenger load and gradient, but it should be of the order of 0.5km or so.

Capacitors would add about 10 to 15% to the cost of a tram and about 0.9 tonne to the weight. The additional weight is apparently taken into account within the claimed energy saving. The unit has no moving parts, apart from the cooling fans, and a service life in excess of 10 years is claimed. To capture the full benefit it would be necessary to take account of its energy saving ability from the outset and adjust the design of the power system accordingly. Any ‘wire-free’ operation, which might have the effect of further reducing the cost of the infrastructure, should be regarded as a useful bonus but not the primary reason for its selection.

Weight: The units would add about 0.9 tonnes to the weight of a typical tramcar.

Re-fuelling: There would be no re-fuelling requirement.

Noise and vibration: There should be no noise or vibration.

Vehicle life: The capacitors should have no effect on the life of the vehicle and might have to be replaced once or twice during a 30 year period independently of it.

Vehicle availability and reliability: There should be no effect on vehicle availability. In principle reliability might be improved as result of the greater operational flexibility provided.

Vehicle compatibility with infrastructure: The capacitors should have no negative effects on the system infrastructure, although Electro-Magnetic Compatibility and related issues would have to be examined. Providing that the design of the power supply system was optimised to function with capacitors there should be an overall improvement in compatibility in that area.

Passenger Capacity: The provision of capacitors would have no direct effect on the capacity of the trams or the system, but the passenger payload may have to be reduced marginally to compensate for the additional weight.

Performance: The capacitor, when fully charged, is capable of moving a tram for some distance. The actual performance available at any point in time will depend on its state of charge and such other matters as the size of the auxiliary load on the vehicle that it is required to support in the event of an interruption of the traction power supply.

Capital and operating cost: The capital cost of the trams would be increased but this should be offset to some extent both by the economies that it should be possible to make as a result to the power system and possibly by leaving some little used facilities unwired. The overall system operating cost should be reduced and the maintenance cost of the additional equipment should be negligible although provision would have to be made for replacing the units at, say, ten 10 yearly intervals. Although undoubtedly of benefit to the environment, it is not yet clear whether the savings in energy costs will repay the additional capital cost involved.

Summary: Traction capacitors have been developed as a means of storing braking energy both from the tram on which they are installed and from other trams on the network. The capital and renewal costs associated with them have still to be established, although the initial indications are encouraging. The equipment has not been developed to provide 'wire-free' operation although it can also have that effect. If the installation of capacitors allows some sections of complex overhead equipment to be omitted, such as emergency crossovers, this may add to the justification. There appears to be no prospect of capacitors permitting wire-free operation over any significant distance within the World Heritage Site at present.

4.4 Fuel Cells

The development of fuel cells for railway applications has been going on for some years although so far without the breakthrough that was originally hoped for. The problems encountered have related to cost, size, power output and the mechanical robustness required for a rail application. In theory the application of fuel cells could combine the advantages of electric traction, including performance and the lack of noise and fumes, with substantial savings in electrical infrastructure.

Fuel cells could be closest in their characteristics to the traction battery option, but without the limitations of range and the need for frequent re-charging that batteries require. However at the present time there is no light rail vehicle or commercial fuel cell system available. An agreement was signed recently in America to develop a 150kW fuel cell drive for a railway vehicle and work is reported to be underway on the development of a 1.2MW locomotive drive.

Due to the fact that these products are still at the development stage detailed information, including cost, weight and performance, is not readily available and so it is not possible to carry out a full assessment. The safety and regulatory implications will be difficult to assess until the details of proven design are available and there is some service experience to support it. The detailed implications for the depot and for handling the substances involved have similarly still to be established.

In addition, the time required to progress them from their present state of development into a commercial product could be considerable. It is most unlikely that this timescale would fit the programme for the implementation of the Edinburgh tram project.

We have concluded that this option should not be taken any further.

4.5 Diesel Powered Trams

This option involves the provision of a diesel engine instead of an electric traction package. The diesel engine would be the only source of power on the tram and would drive the wheels either directly by means of a mechanical transmission or indirectly by means of an hydraulic or electric transmission.

A number of diesel-mechanical vehicles, such as the Regio Sprinter, have been developed in recent years primarily for the operation of local secondary railway lines in Germany although they are also used more widely. They were developed for lightly trafficked lines as a way of facilitating tramway style operation and infrastructure mainly to reduce the cost of operation. They have the ability to operate over sections of street track for short distances although there are few examples of this being done. Such vehicles can offer an economic solution for the operation of lightly used local rail lines and possibly for extending them further into an urban area as a tramway. We have been unable to identify any examples of such vehicles being used to operate an urban network.

The cars that are available are generally built to heavy rail dimensions although they have an intermediate floor height of about 400 to 450mm for loading from low platforms. Since they have been designed to operate over lines built to railway geometry they are not suitable for operation over steep gradients or round sharp curves. The transmission arrangement and the number of powered axles would preclude an application like Edinburgh.

Summary: Diesel trams, although in principle available, do not have the level of performance, the door layout or the internal arrangement necessary for the operation of an urban tram service carrying dense passenger flows at close headways between closely-spaced stops. In addition due to limitations on the number of powered axles and the arrangement of the transmission such vehicles are unsuitable for operation through tight curves and over steep gradients (e.g. down to 25m radius and at between 6 and 10%). The use of such vehicles would raise many issues concerning statutory approvals and regulation.

An all-diesel vehicle has not therefore been examined any further.

4.6 A Diesel Hybrid Vehicle

An alternative to the use of a straight diesel powered tram would be a diesel/electric hybrid vehicle. Under this arrangement an electric tram designed to operate from an overhead power supply would be fitted with an auxiliary diesel power unit and generator. The tram could operate either from an overhead power supply where one is available or from its own auxiliary diesel engine and generator on unwired sections. Another approach would be to fit a traction battery to the car and use a smaller diesel engine, running continuously, to charge the battery. The tram would be powered from the battery on unwired sections.

The same approach could be used with a petrol engine or using alternative fuels such as LPG.

Although the petrol or diesel hybrid approach has been applied to trolleybuses to increase their range and performance when operating away from an overhead supply, it has not so far as we are aware been applied to a tramway.

There are a number of examples of hybrid diesel or LPG and battery powered buses (typically weighing up to about 14 tonnes fully laden), mainly for pilot schemes, but these technologies have still to be applied on a commercial scale to rail vehicles as large and heavy as a tram which can weigh from 60 tonnes to 75 tonnes depending on its length. In addition the safety implications for such an application have still to be considered. In this analysis therefore, a conventional tram modified to operate either from an overhead supply or a diesel engine, has been taken as the basis of comparison.

Dual supply overhead and diesel trams are used in a small number of cases on systems such as Kassel and Nordhausen in Germany. In these cases more or less conventional low-floor trams have been adapted to operate either from an overhead supply or from a small on-board diesel engine. The diesel engine is used to allow the trams to operate over a non-electrified local railway line.

The Nordhausen diesel trams run for about 3km in electrified mode and then for 12km in diesel mode on the section of railway that they share with local trains. In this instance three new trams for the urban tram fleet were supplied in a modified form to operate the railway service. Although the concept appears to work well it is a specific response to a specific local need. The trams do not operate in diesel mode when traversing the tramway system and the infrequent local rail service is clearly quite different from an intensive urban tramway.

For the Edinburgh system it has been assumed that a hybrid diesel/electric car would operate from an overhead supply for most of the route length of either Line 1 or Line 2 and from its on-board diesel engine and generator only within the World Heritage Site, a distance of about 2.0 km. It has been assumed that the diesel engine would be shut down when travelling over the electrified sections, rather than kept idling when not being used. This would be more energy efficient and attractive for passengers than the alternative of keeping it running all the time, but would mean that the starter motor and battery would become the potential weak link since the tram would be entirely dependent on them twice in each round trip.

The fact that a small number of such hybrid cars are already in commercial service may be regarded as “proof of concept” but it does not answer the detailed questions that would arise for a system such as Edinburgh. The Nordhausen cars are only 19 metres long, compared with the 30 or 40 metres being considered for Edinburgh, and are equipped with a diesel engine capable of delivering the equivalent of 180 kW at 4,000 rpm. When operating in electric mode they have a nominal rating of 400kW.

A 30m tram of the type required for Edinburgh would typically have between 400 and 500 kW of installed power (more if the duty cycle and route profile required it). The 40m cars for systems such as Dublin, Bordeaux and Brussels are rated at up to 720 kW.

The power rating of the Nordhausen trams when in diesel mode is thus a reflection of the different requirement created by a lightly graded railway line with widely spaced stations compared with an urban tramway. It is clear that a vehicle of this type would not come anywhere near to meeting the performance requirements for an intensive urban tramway operation.

Weight: The diesel unit adds about 0.3 tonnes to the car weight. A hybrid vehicle with a battery would probably weigh significantly more, say 0.7 tonnes.

Re-fuelling: For the type of duty envisaged, under which the diesel engine would be used for only 4.0 km in each round trip, overnight re-fuelling at the depot would be adequate. The fuel tanks would add to the weight of the hybrid vehicle and to the space required.

Noise and vibration: Although the engine compartment could be sound-proofed as with a modern diesel train, there is no doubt that some additional noise and vibration would be apparent.

Vehicle life: The life of the tram would probably be affected very little by the conversion, although some complications might arise as it got older. The diesel engine itself and its auxiliaries would have a more limited life and it should be assumed that the tram would be re-engined up to three times during its life.

Vehicle availability and reliability: Availability of a diesel/electric hybrid vehicle would be lower than for its straight electric alternative. The diesel engine and other additional equipment would affect both availability and reliability. It is unlikely that availability would exceed say 85% compared with an availability of about 95% for a conventional tram.

Vehicle compatibility with infrastructure: The use of diesel-powered trams would raise some environmental concerns and detract from the ‘ambience’ of the system, but they should be compatible with the basic infrastructure. Some re-design of the depot would be necessary, safety implications would have to be re-examined in a number of areas and it would be necessary to ensure that their performance would be adequate under all circumstances.

Passenger Capacity: The passenger capacity of the trams would be reduced by the equivalent of about 14 passengers under peak loading conditions due to the loss of floor space. The provision of uprated diesel engines, to come closer to matching the performance of the trams in electric mode, would add substantially to the weight and the space required. The passenger capacity would be reduced correspondingly.

Performance: The performance of the diesel-electric hybrid when in its diesel mode would be significantly less than the alternative electric tram.

Capital and operating cost: Both the capital and the operating costs would be significantly greater than for the conventional alternative.

Summary: The hybrid diesel/electric option either with or without the addition of a traction battery is essentially the same as all the other options based on the same principle but which use alternative fuels, such as LPG. The addition of a battery might permit performance to be improved or the size of the diesel engine reduced but in either case it would be at the expense of additional weight and cost.

By including its own prime mover, this option does not create the same degree of uncertainty as to its range and reliability that some of the other on-vehicle options, such as flywheels and capacitors do, but it would be inferior in terms of its performance, passenger capacity and general environmental impact. A hybrid vehicle would be considerably more complicated than a conventional electric tram and would be less reliable and have a shorter economic life. In addition its direct operating and maintenance costs would be significantly higher than for an electric vehicle. Though suitable for a track sharing role on local railway lines in outer areas, for which it has been designed, it would be quite unsuitable for the operation of high frequency services at the heart of a prestigious urban tramway.

5 OFF-TRAM OPTIONS

5.1 Ground Level Power Supply

Systems of ground level power supply were used on electric tramways from the earliest days and until about 40 years ago. These were of two main types: systems that supplied traction power to the tram by temporarily energising a series of discrete contacts in the highway as the tram moved along (surface contact) and systems that supplied power to the tram from a continuous protected conductor installed below the highway (conduit).

The first of these systems (surface contact) ceased to be used after quite a short period. This was mainly because the system relied on raising and energising discrete contact studs as the tram moved over them and de-energising and retracting them as it moved on. It proved virtually impossible to do this safely and reliably on a regular basis.

Systems of the second type (conduit) were much more extensive and continued in operation for several decades in major cities such as London, Paris, Washington and Bordeaux until the first generation tramways was abandoned. This method of current collection required the provision of a continuous slot in the highway which greatly increased the cost of track construction and maintenance and was regarded as a hazard to other road users.

The conduit current collection system has not been used for over forty years and no work has been done on its reintroduction for any of the large number of new tram systems that have been planned and built worldwide in recent years. It would not now be possible to reintroduce the system in its previous form, as it would not meet present safety standards. The cost and timescale involved in re-engineering it would be substantial, even if a workable arrangement could be identified.

Although surface contact systems (as opposed to conduit) ceased to be used more than a hundred years ago, a considerable amount of work has been done by a number of contractors, mainly in France and Italy, in recent years to re-invent it for tram and bus systems. Ansaldo developed the STREAM surface contact system that was purchased in 1998 for a single line in Trieste. So far as we are aware the system has not achieved an independent safety validation and is not in public service.

The most significant work has been carried out by Alstom in France, mainly as result of their acquisition of the Innorail company. The resulting system, called APS, was selected by Bordeaux after they had considered the alternatives, including STREAM, and has now been in commercial operation on the new tramway there for about two years. Other possible applications are being considered in France but so far it is the only one that has been implemented.

The Bordeaux tramway has been examined to establish its characteristics and performance as part of the technology review for Edinburgh. This is the system that is considered in the rest of this section.

The system that has been applied in Bordeaux consists of a single central switched steel conductor rail about 200mm wide which is installed some 12mm above the height of the two running rails. The conductor rail is divided into alternating 8 metre ‘energisable’ and 3 metre ‘dead’ sections. The movement of the tram along a section of the track switches on the traction power to each of the 8 metre sections in turn as the tram runs above it. The tram collects current via a pick-up shoe mounted on one of its trailer bogies as it passes over the energised section of rail. The presence of the tram above the energised section ensures that it is not accessible to the public while it is energised. Before the tram leaves the section of rail and leaves it exposed again the power is switched off. By that time the tram is running above the next section which is also energised to maintain continuity of current collection.

The complete ground level power system is safety critical and subject to the creation of a ‘control loop’ between the tram and the track section concerned. Each track section is also monitored via the tramway SCADA network. The arrangements for switching and control become more complex where crossovers and junctions are involved.

A confidential report on the system is set out in Appendix A. The main points that emerge are that:

- The system appears to perform the basic function for which it was acquired in that a frequent service is maintained without overhead equipment in the central area.
- However considerable teething problems have been experienced although these may now be becoming less significant.
- The conductor rail must be installed about 12mm higher than the running rails to ensure good drainage. This requires a special profile for the road with a secondary camber between the running rails. This is likely to cause problems for road traffic on shared sections, particularly as British practice (following problems that were experienced in Sheffield) has been to off-set the traffic lane in relation to the tram track under such circumstances in order to reduce the risk of cars running on the tram rails with their relatively low skid resistance.
- Depending on the degree of segregation chosen this could apply to about 2 km of route and a number of road junctions within the World Heritage Site.
- Bordeaux does not experience significant snow and ice and as a result the roads are not gritted in the winter. The problems that are likely to arise in Edinburgh from the presence of snow and ice include the additional risk of skidding on the smooth surface of the conductor rail and the corrosive effect of the ingress of salt and water on the rail assembly.

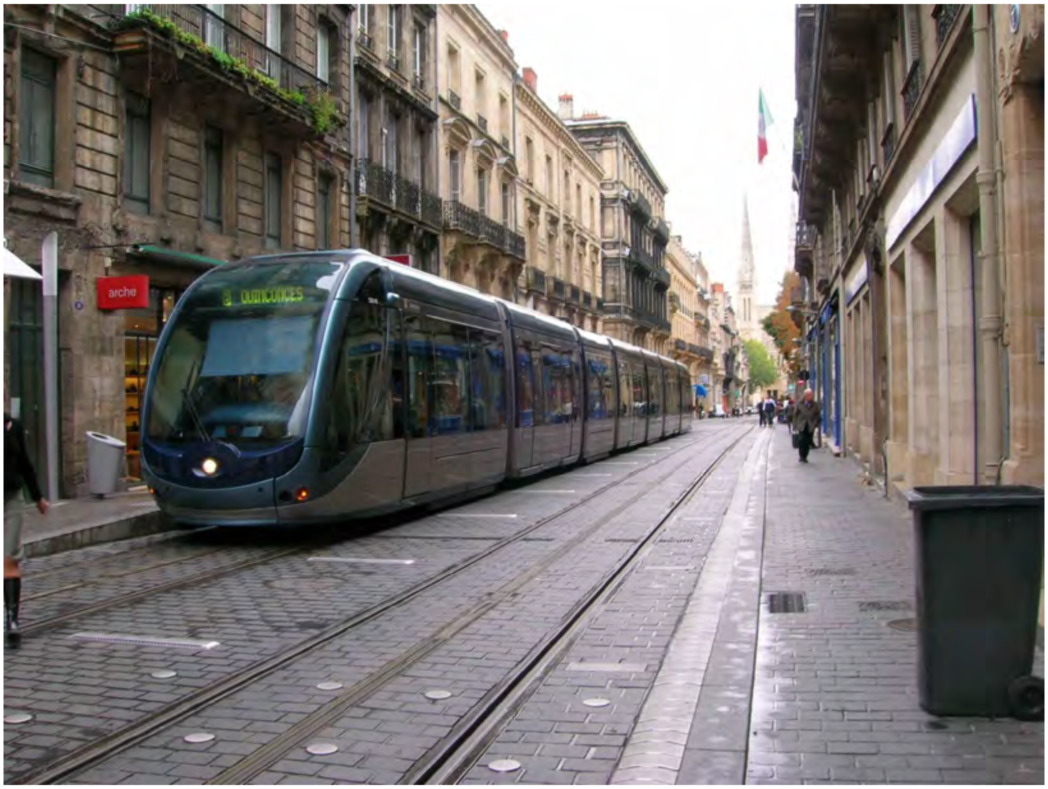


Figure One

The installation in the city centre of Bordeaux is shown in Figure One.

Experience in Bordeaux in a more benign climate than that of Edinburgh is that to date the system has been relatively unreliable. A typical modern overhead system may be expected to experience a problem which delays the service for 5 or more minutes about once every 5,000 hours or more. The APS system in Bordeaux was quite unreliable in the early days, however after 22 months in regular service it caused such a delay less than every 1,000 hours. It may be assumed that the initial problems, which mainly arose from the water-proofing of the connection boxes installed in the roadway at 22 metre intervals, have now been resolved.

The Bordeaux trams are limited to a maximum speed of 50 k/mh (30 mph) when operating in APS mode for reasons of safety and are not able to brake regeneratively in this mode (although that was part of the original specification). In addition to having the APS collector gear on one of the trailer bogies the Bordeaux trams also carry about 0.8 tonne of traction batteries and a fully rated braking resistor. The battery is to allow them to continue to run when sections of the APS power supply system have failed locally. As with the other battery options already considered above this does provide some operational advantages.

The installation of the first system outside France in the wetter and frequently colder environment in Edinburgh would almost certainly generate a new series of problems. While these would probably be overcome in time, the cost of doing so and the effect on service reliability in the interim might be substantial. This could adversely affect the image of the tramway and it commercial performance during the all-important early stages.

Weight: The weight of a standard tram would be increased by about 3%, due to the traction batteries and current collectors.

Re-fuelling: There would be no requirement for re-fuelling

Noise and vibration: The use of the APS system would have no significant effect in terms of noise and vibration although the noise of the ground power current collector would be noticeable when operating in that mode.

Vehicle life: There should be no effect on vehicle life, apart from the need to replace the battery at intervals.

Vehicle availability: Vehicle service availability would be slightly less than for a conventional tram due to the batteries, ground power current collector and associated control circuitry including the safety critical vehicle-mounted switching unit.

Vehicle compatibility with the infrastructure: The vehicle and the infrastructure would have to be designed as a unit and there should be no compatibility issues. The tram could make use of other suitable secondary technologies such as capacitors or batteries if advantageous.

Passenger Capacity: The capacity of the trams should not be affected although the implications for the passenger payload of the additional weight would have to be assessed.

Performance: The top speed of the tram would be significantly reduced, to 50km/h, when operating in APS mode, but this should have little impact within the World Heritage Site. A few seconds delay would be enforced during the changeover from overhead to APS current collection.

Capital and operating cost: The capital and operating costs will be substantially greater than for a conventional system. It is difficult to quantify the additional cost involved because of the method of procuring such a system for which there is only one supplier. Indications so far are that Alstom would not be prepared to sell the APS system without the trams to go with it. The extent of any re-design that might be required and arrangements for obtaining safety approval for its use in the UK are also difficult to assess at present.

Since the installation in Bordeaux has still to settle down at an acceptable network-wide level of reliability, it is not clear what the long-term maintenance costs will be. It is clear however that whatever the final figures the costs will be significantly higher than for a well-designed overhead system, which is normally a relatively low maintenance item.

Improving energy efficiency by means of regeneration has been one of the major advances of the past couple of decades. The inability of trams to regenerate when in APS mode and thereby save energy will add significantly to overall power costs.

Summary: The APS ground power system was selected by Bordeaux after extensive research as the best available option if overhead was not to be used. It is however more expensive to construct than the conventional alternative and is likely to remain so whatever refinements are carried out to it. It meets the objectives that Bordeaux set for it but has not yet achieved a level of operational reliability equivalent to that of a modern overhead system.

While undoubtedly subject to very high levels of safety assessment and independent validation, including advance testing on another French tramway, it is unclear precisely what process would be required to obtain approval a for its use within the road in the UK, but it would certainly involve HMRI and the City of Edinburgh. Other agencies are also likely to be involved and interest groups will also have a view. The additional safety issues that would be raised by the very different climatic conditions in Edinburgh also mean that very little of this work could rely on the precedents that have already been established in Bordeaux. It would involve a fresh start. Resolving these issues, if they are capable of being resolved, would be likely to involve a number of agencies and take some time. It would not be compatible with the project programme.

A further complication is that APS is a proprietary system which is under the control of Alstom. Present indications are that they would be unwilling to sell the APS system including the current collection and safety-critical track section switching equipment for installation on a fleet of trams unless they were also supplying the vehicles. It is unclear how this could be reconciled with **tie**'s procurement strategy.

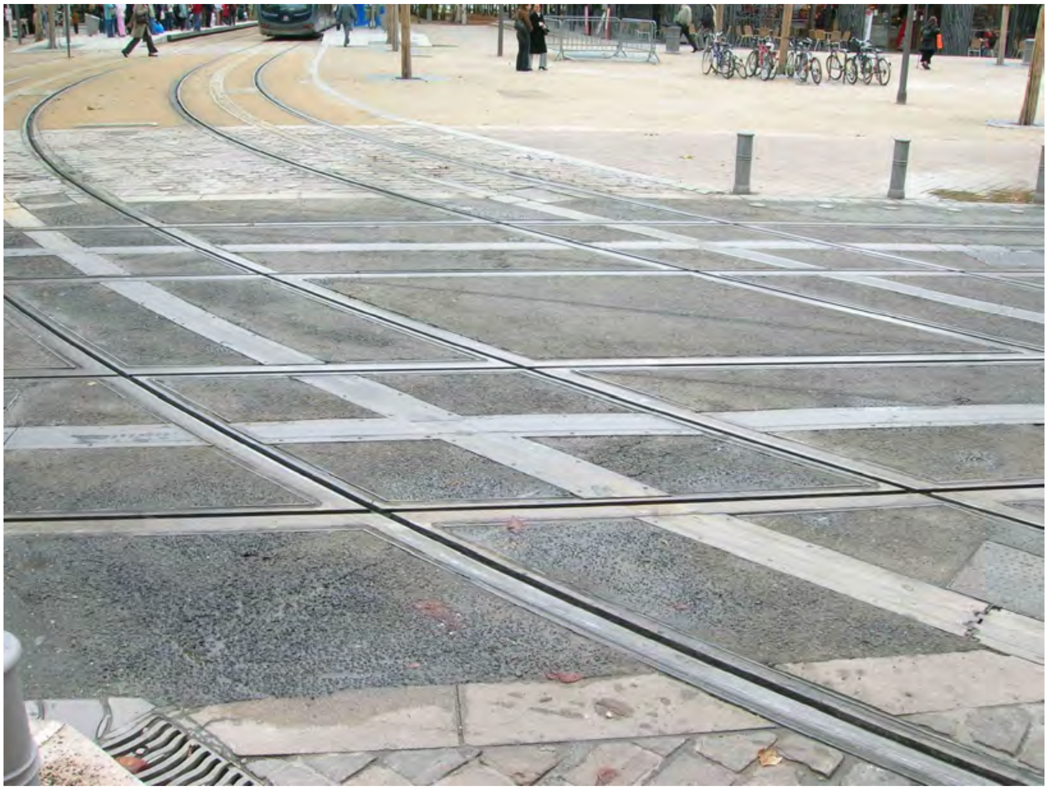


Figure Two

While the APS system undoubtedly avoids the need to install overhead equipment in the areas where it is employed, it is not without its own visual impact. This is due to the need to install the contact strip throughout such sections and the control boxes every 22 metres. Other boxes are also sometimes required locally. Although such matters are essentially subjective, the visual impact is clearly significant at ground level when compared with a pair of tram rails. The effect at a tramway junction is shown in Figure Two

5.2 Other Options

As noted in Section 3 above, although there have been many developments in the field of tramway engineering in recent decades and these have led to significant gains in performance and operational efficiency, virtually all of them relate to the refinement of conventionally powered trams. There has been little work on infrastructure based options apart from the APS system. Even here the city of Bordeaux has had to take responsibility for getting the product developed. The options that they examined and rejected several years ago, such as the Ansaldo contact system, do not seem to have progressed in the interim. Thus there does not appear to be any equivalent alternative system available.

Although in theory it would be possible to re-invent a system such as conduit current collection using modern materials and construction methods this has not been done and there is no prospect of such a development being available within the timescale required for the Edinburgh Tram Network. Any new system would also have to go through a long process of development and safety certification.

An alternative to overhead electrification which was used in Edinburgh for several decades is that of cable traction. With this system a tram is pulled along by a moving cable running at constant speed within a slot in the road. The car is attached to the cable by means of ‘grip’ device which allows the cable to be ‘slipped’ on the approach to tram stops and junctions and picked up again in order to accelerate again.

Edinburgh had a large cable operated tramway until it was electrified in the 1920s and essentially the same technology is still in use on the predominately tourist cable cars in San Francisco. In slightly different forms it is used in one or two other places including, without the grip mechanism, the Great Orme Tramway at Llandudno. This operates to a limited extent within roads that are used by local traffic. The San Francisco cable car system was largely re-built a few years ago and some more modern construction techniques were used in the process. The whole process served, however, to show how complex, expensive and disruptive such a system is to build.

The re-introduction of such a system in a UK context would raise major safety issues. In addition much of the technology would have to be re-invented and hauling large and relatively heavy light rail vehicles by this means, as opposed to the light wooden bodied cars formerly used would be a major challenge. Other disadvantages are that operational performance would be restricted due to the use of a relatively slow constant speed cable, power would still be required on the cars to power their auxiliaries and the inter-working arrangements between the two lines and Line 3 in the future would raise some significant issues.

In the 1980s and 1990s a considerable amount of development work on modern cable hauled systems was done in France, mainly by the SK Soule company. Ski lift technology was used as the basis for these developments. Although some installations were built ambitious plans for a number of short cable-operated lines in Paris using a large number of relatively small cars have never been realised. It appears that major technical and financial problems were encountered particularly with a proposed system for Charles de Gaulle airport and that as a result no further development has taken place. Internationally a number of cable hauled airport shuttles have been implemented but these are all fully segregated and do not represent public transport applications.

None of the applications either historically or more recently have involved the mixed use of cable haulage and conventional overhead on different parts of the same network.

The main lesson that can be drawn from this experience is that even where there is an established local market and substantial funding it is very difficult to successfully adapt established and proven ski-lift technology to a public transport application. In the context of the Edinburgh tramway the obstacles to be overcome in putting forward any form of non-standard and unproven technology are very much greater.

There do not appear to be any other systems or technologies which merit detailed consideration for Edinburgh.

5.3 Roles and Responsibilities

The roles of the SDS project team members are defined below:

Project Director

- Corporate responsibility for the delivery of the Project;

- Jointly responsible for procurement of project team and its activities;
- Strategic review and advice regarding project implementation.

5.4 Communication and Reporting Lines

Communication with **tie** and external organisations will be in accordance with the communications protocol as described in the Project Communications Plan provided in Doc Ref ULE90130-SW-SW-PPN-00008 which will form Appendix H of this Project Management Plan. **tie** Communications Manager has confirmed this plan will be issued by **tie** following consultation with PB as the SDS provider.

The lines of communication will be in accordance with Fig 3.4 below.

6 EVALUATION

6.1 Strengths and Weaknesses

The options that have been examined represent all those that are potentially available for a wire-free traction system. There are only a limited number of ways in which the provision of wire-free traction could be approached and while there are other possibilities these are essentially variations on the same themes.

The main features of each of the options are summarised in the table below. They are evaluated against the standard criteria in Section 6.2.

Table One

Option	Strengths	Weaknesses
Traction batteries	- Ability to operate off-line for a limited period. - Can provide a back-up to overhead traction in the event of power failure	- High weight and first cost. - Limited operating range. - Relatively high maintenance requirement and high maintenance cost combined with limited battery life.
On-vehicle flywheel	- Improved energy efficiency. - Limited ability to operate away from an overhead supply.	- Not yet commercially available. - At an early stage of evaluation. - If offered likely to be as a means of improving energy efficiency rather than for off-line capability. - Maintenance and safety implications have still to be disclosed.
Fuel cells	- Ability to deliver high levels of power as and when required	- Not yet commercially available for rail applications. - Likely to be relatively expensive in first cost when available - Maintenance and life cycle costs not available - Could be safety implications
Capacitors	- Potential to deliver significant energy savings on a network basis. - Some ability to operate away from an overhead supply - Have been in revenue service on a limited basis for over two years and have been reliable.	- Additional cost and weight. - Limited performance away from the overhead. - Life of units still to be established - Maintenance implications have still be established but experience is significant and increasing
Diesel	- Completely independent of power infrastructure.	- Additional cost, weight and maintenance. - Loss of passenger space - Increased cost and complexity of depot - Limited life of mechanical parts and effect on life of tram. - Not available in a low floor tram format - Unlikely to be compatible with alignment geometry - Performance more suited to a suburban or regional railway. - Would compromise the design of tramway infrastructure.

		- Noise and pollution would be greatly increased - Overall quality of the system would be reduced
Diesel as auxiliary power	- Could be used in conjunction with one of the other alternatives, such as batteries, to extend range.	- Some loss of passenger space and payload - Loss of performance - Best suited to allow trams to operate onward extensions of little used railway infrastructure rather than in city centres - Could provide a dual mode capability operating on engine/battery in city centre and from overhead supply elsewhere - Would add to the cost and complexity of the depot
Liquid Petroleum Gas	- An alternative fuel source with 'greener' characteristics	- Not realistically available. - A sub-option to diesel traction.
Surface contact system (APS)	- Freedom from overhead equipment over substantial parts of the route.	- Obtaining safety approval in a UK context from both road and rail safety authorities could be very difficult and time consuming. - Differences in climatic conditions (particularly snow and ice) compared with Bordeaux could be a major problem. - Capital and operating costs would be higher. - Proprietary nature of system likely to preclude competitive procurement of infrastructure and trams - Would be more visually intrusive at surface level particularly in areas with 'heritage' paving - Some operational limitations
Alternative technology - Cable	- Long-established technology and used extensively in Edinburgh in the first part of last century - Used in a different form for dedicated shuttles and has been proposed for urban applications.	- Safety approval likely to be a major problem despite historic precedents. - Operational performance would not match requirements. - Would be very expensive to install and maintain. - Reliability and extendability would be major issues. - Not compatible with mixed use on different parts of the network.

The Edinburgh tram system is a prestigious project which will be required to deliver a high-quality reliable public service for the capital city of Scotland. As such, while innovative solutions may deliver some benefits, any technologies used must be fully proven, low risk and capable of delivering a reliable service in a cost-effective manner. In addition they must be reliably deliverable within the project timescale and not expose the programme for the rest of the works to undue risk.

From the summary in Table One above it can be seen that although the details vary from one option to another all of them have substantially more weaknesses than strengths. In addition none of the weaknesses are trivial and none of the options stand out as being very close to being acceptable for an urban tram application.

Although 'lack of performance' has been referred to where it is an obvious weakness, the lower level of reliability that all the options would provide should also be noted. Another feature that would apply to most of the options is that of having to change over from time to time from the overhead system to an alternative. In the case of the APS system this would take place in a tramstop at the beginning and end of the APS section. The stops used for such changeovers would be equipped with both overhead and the ground power conductor. The process would take about half a minute and suitable interlocks would be built into the tram to avoid both systems being in use at the same time. Whether this would avoid all possible causes of human error is unclear. One of the reasons why little used crossovers have been wired on some electrified railways is because of the near inevitability of trains being driven across them with the pantograph raised at some stage, with consequent damage to both the overhead and the train.

Changeover arrangements and protective measures would have to be devised for each of the other alternatives. While arrangements such as simply ramping the contact wire out of running at the beginning of an unwired capacitor or flywheel section and bringing it back down again at the end might sound straightforward, they would produce other complications and would be likely to make the overhead more rather than less obtrusive at the changeover point and the trams more obtrusive throughout the unwired sections due to their pantographs being fully extended.

There would be problems obtaining a number of the options particularly within the project timescale, in addition others such as the APS system are unlikely to be available competitively without distorting the procurement process

6.2 Assessment

The different options have been assessed under the standard headings set out in Technology Review Scoping report and in Section 2 above.

The ranking of the various options against the standard criteria is summarised in Table Two below. In the evaluation process 'quality' has been taken to mean quality in the specific context of how each of the possible solutions would be perceived if applied to the Edinburgh tram system as currently defined and 'risk' to mean the risk to the project in terms of the overall performance of the tramway if that option were to be implemented.

The headings that have been used in the table are:

- Functionality – ability to deliver against the requirements specification
- Availability – both for installation and ongoing operation
- Impacts – including construction and visual
- Safety
- Hazards
- Costs – both initial cost and ongoing cost
- Risk profile – in the first instance and subsequently
- Reliability, Availability, Maintainability And Safety (RAMS)

Table Two

Solution	Time / Availability	Cost	Quality	Safety	Risk	Aesthetics	RAMS
Battery	Yes	Medium/high	High	Good	High	Good	Good

Flywheel	No	Medium	Medium	Unknown	High	Good	Un-certain
Fuel Cell	No	High	Un-known	Unknown	Very high	Good	Un-certain
Capacitor	Yes	Medium	High	Good	High	Good	Good
Diesel	No	Medium	Very low	Medium	Very high	Poor	Poor
Diesel hybrid	Yes	Medium	Low/ Medium	Good/medium	Lower	Medium	Medium
APS Surface contact	Yes	Very high	Medium	Requires clarification in the local context	High	Good apart from effect on paving	Poor
Cable	No	Very high	Low	Medium	Very high	Moderate	Very poor

From the table it will be seen that none of the options can be given a ‘clean bill of health’. In some instances this is with respect to their suitability for meeting the basic objective of being able to operate for a worthwhile distance away from an overhead wire. In other cases the qualifications relate to more basic matters such as safety.

The alternatives that require extensive special infrastructure, such as APS and cable traction, are the most expensive. The alternatives that that involve the installation of an independent prime mover on the tram are among the cheaper ones to implement, though still more expensive than the a conventional overhead system. However, they diverge very substantially from the specified level of performance and reliability.

7 SUMMARY AND CONCLUSIONS

The physical extent of the tramway within the World Heritage Site means that because of their strictly limited range and performance many of the options would not be able to provide a useful wire-free system even within a limited area and can therefore be ruled out. Unfortunately, the options that fall into this category are those that might have produced some secondary benefits, primarily in terms of energy conservation.

None of the alternatives look particularly attractive by comparison with a conventional well designed overhead contact system, even without their inherent limitations of range and performance. If overhead is taken as the base option then all the alternatives suffer from the fact that they would be more expensive to build and maintain and would impose operational restrictions. Reliability and availability would be worse than for the base option and the longer-term implications of the additional equipment involved, including life cycle costs, are unknown in many cases.

Some of the alternatives would also produce an environmental impact, such as the noise and fumes from a diesel engine or the additional equipment installed within the paving, although others such as batteries would not have these negative effects. There would be safety implications from the use of some of the alternatives, such as the additional risk of skidding created by the APS conductor in the road surface, or the potential hazards associated with high speed flywheels or high temperature fuel cells.

A number of the solutions would involve a reduction either in the space available on a tram for passengers, due to the additional volume of equipment to be housed, or in the passenger payload that could be carried. The passenger payload would have to be reduced to keep the trams overall weight, axle loading and weight distribution within the design limits.

For anything other than a solution that involves adding equipment for energy storage or supplementary power to a standard tramcar there would be major problems in obtaining a suitable vehicle within the required timescale. The cost of modifying a standard tram would be likely to be significant: anything more radical could be very expensive, assuming that there was a supplier sufficiently interested to quote for it. In the UK market this in itself is a large assumption.

Virtually all the options would create regulatory and ‘approvals’ issues to a greater or lesser extent. Solutions that centre on energy storage on the tram, such as batteries and capacitors, are likely to raise a lot fewer issues of this type, but even here the possibility of a tram becoming stranded away from the power system in the city centre is likely to be cause of concern to other organisations including the police, the emergency services and the bus operators. The level of disruption that this could cause if it occurred at a key road junction in the rush hour could be considerable.

Because the alternatives have weaknesses and drawbacks which vary in nature they are difficult to rank objectively. Since the implications of having to gain approval to the use of new equipment of a novel type such as APS or hybrid traction are particularly onerous, those options which simply add another piece of equipment to a more or less standard tram, for example for energy storage, must be regarded as the ‘least risk and ‘least bad’ overall.

Of the solutions that involve adding equipment to an otherwise standard tram, super capacitors seem to offer the greatest potential benefit, primarily because of their contribution to energy conservation together with their limited off-overhead capability.

At the present time there does not appear to be a straightforward alternative to the system-wide use of an overhead contact system. For that reason it appears that work should proceed on the basis that the whole of the system should be wired, at least initially. In parallel with that, the tram procurement process could take into account the possible wider benefits from the use of super capacitors and test the market to see what is on offer at the time, at what price and with what guaranteed level of performance. It might then prove possible, for example to leave certain emergency crossovers unwired and to use the energy storage system when operating through them, although that may involve more complication for little advantage.

8 APPENDIX A – REPORT ON THE BORDEAUX APS SYSTEM

To:	Chris Mason	**At:**	Edinburgh Project Office
Copies to:	Paul McCauley Ian Sproul	**At:**	
From:	John Baggs	**At:**	
Date:	18 October 2005	**Ref:**	
Subject:	**BORDEAUX - APS GROUND POWER SYSTEM**		

Confidential Report on visit to Bordeaux Tramway – 14th October 2005.

Present:

Roger Jones	–	**tie**
Thierry Ficat	-	‘Mission Tramway’, Bordeaux Municipality
Christian Buisson	-	Transdev France
John Baggs	-	SDS

Purpose of Visit:

The purpose of the visit was to inspect the APS surface contact system installed in Bordeaux and to establish what the operational experience with it has been.

Background:

M. Ficat gave an introductory talk on the subject of the Bordeaux tramway and the political background, followed by a presentation on the system. He offered to supply a copy of the presentation which Transdev will circulate when it is available.

The Tramway:

Phase 1 consisting of 3 lines and 24.5 kilometres was opened in 5 stages between 21st December 2003 and September 2005. Phase 2 consisting of a further 19 kilometres will be opened between 2007 and 2009. The total cost of the network will be Euro 1.03bn at 1999 prices. A fleet of 70 trams is being procured at a cost of Euro 169M. These are predominantly 40m long although some 30m trams are operated at present. The cost of Phase 1 was Euro 550.34M, or Euro 22.43 per kilometre, which appears attractive given the investment in the city centre, workshops and other items.

Other costs were Euro 3.81M per track/km, 0.34M per substation, 0.5M per OLE track/km, 1.5M per APS track/km and 2.4M for the complete signalling system. A total of 120 separate contracts were awarded.

One depot and workshop (cost Euro 31.6M) has been provided for all three lines, although a separate stabling facility will be provided as part of Phase 2. Depot journeys are time consuming because of the indirect routing involved and because they have to observe all tram stops. This is a contractual issue with Alstom who argue that maintenance access to the APS system is severely restricted since trams are moving on the system for 221/4 hours rather than the 20 hour operating day that was specified.

The system and the construction programme have been configured so that it will not be necessary to go back into the central area to carry out further construction work in the future although both Lines A and C terminate on the northern edge of the central area ready for onward extension into the suburbs. Much environmental improvement work was done in the city centre at the same time as the construction of the tramway, although it was not clear to us how the separate budgets had been allocated for this.

The construction of the tramway involved the first application to a tramway of the new French Safety Regulations. Although they were not in force at the time when the process started it was decided to work to them from the outset. The broad principles appear to follow a CDM pattern except that all aspects of the project have to be reviewed by independent experts approved by the government. Some 300 reports had to be assessed. A separate file has to be maintained for each innovation such as the APS.

On Phase 2 there will be a level crossing of an SNCF electrified line and a swing bridge over the river – both are treated as innovations. There was some 'semi in-house' involvement in the process in respect of the safety of the overall system due to the need for specific knowledge (Certifer were responsible for the tram and Ligeron for the infrastructure), but this would not be permitted in future.

Due to the fact that they are likely to end up with two teams of experts disagreeing, M. Ficat said that the French systems now believe that the independent safety review will cost about 1% of the overall project cost.

The APS System:

The system had been selected because of the following:

It was required by the French Ministry of Culture

The Fire Brigade insisted on it to maintain access to the face of buildings in narrow streets

Many old buildings are too low and the stonework is too weak to support OLE

There was strong political support for a 'wire-free' system.

The centre of Bordeaux is a World Heritage Site, though this does not appear to have been a direct influence.

Three alternative wire-free current collection systems were examined, including one developed by Ansaldo, before the Innorail APS system was selected. All of them were at the 'concept' stage. Innorail were subsequently acquired by Alstom.

The development of the system was funded by Bordeaux and the technology was proved initially on a 1km segregated section of tram route 68 in Marseilles.

Achieving a high standard of safety was seen as of paramount importance before the system went into service and the independent safety certification was achieved with 12 months of the award of contract. Reliability was given less attention at that stage.

A number of operational scenarios were examined as part of the safety evaluation and special operating procedures developed for dealing in a safe manner with matters such as a derailment on the APS section. Operation of the tram's emergency brake isolates the APS system. A four monthly meeting is held with the Safety Authority to review experience with the system, any incidents and outstanding matters. The steps being taken by the contractor to deal with outstanding matters are examined at these meetings.

The contract for the trams and track system was awarded to a JV of Alstom, Spie and Cogifer. M. Ficat thought that much less effort had been put into adapting the tram initially than was actually required. The problems with the tram related mainly to such matters as the traction batteries and the support of auxiliary demands such as the air conditioning. The battery was supposed to be rated to enable the tram to be driven at a speed of up to 60km/h and for a distance of up to 1400m. In practice because of problems changes have been made to the trams auxiliary circuits and all the batteries are currently being replaced by Alstom after 2 years.

Alstom have a 10 year fixed price contract for the maintenance of the APS system.

The present lengths of the three lines and the proportions with APS are approximately as follows:

Line	Overhead Current Collection	APS Current Collection	Total Phase 1	Planned Total including Phase 2
Line A	**8.66**	**3.78**	**12.44**	**19.90**
Line B	**4.14**	**5.16**	**9.30**	**15.40**
Line C	**1.33**	**1.47**	**2.80**	**8.00**
	14.13	**10.41**	**24.54**	**43.30**

It is expected that Phase 2 will involve between 10 and 13km of additional APS current collection.

Apart from the conductor rail, the installation in the street involves the provision of a box every 22m to house the CA unit. This is a modular assembly which is located at a short neutral section and which houses the control circuitry and the 750V switches which supply the two 8m long energised sections to each side of it. It contains the control logic for energising and de-energising the two sections fed from it and is regarded as a safety-critical item which is removed and worked on only by Alstom.

The rail is supplied as a factory made unit and is formed on site to fit the horizontal and vertical curvature. This was described as being a relatively easy operation. The minimum curve radius on the system is 18m. Some of the trackwork that has been installed using the APS system is relatively complex with crossovers, flat crossings and double junctions. The junction of lines B and C involves a four track tram stop and a skew crossing of the two lines with a separate link for depot workings.

The general standard of track construction including rail welding is exceptionally high and the cars give a quiet smooth ride on both street track and segregated sections whether paved or grassed. On APS sections the ‘clack-clack’ sound of the current collector is noticeable in the vicinity of the trailer bogie that it is mounted on.

Trams change over from OLE to APS and vice versa at a tram stop. The operation is carried out by the driver as passengers board and alight. At off-peak times when fewer passengers are around at these locations this extends the stop time by a few seconds. APS is installed in long sections running outwards from the centre of Bordeaux. Some short sections were installed in the suburbs so that the different municipalities could each claim to have a section of APS. It is possible that some of these short isolated sections, which have no real justification, will be converted to OLE in due course.

All APS sections are centrally monitored via the scada system. Apparently the driver does not normally notice the loss of power for one or two sections. In the event of a tram coming to a standstill on a failed section the driver has to operate the battery changeover switch: the tram then reverts automatically to APS as soon as it reaches a live section.

Operational Performance:

The operation of the tram system is impressive although Roger Jones had observed some poor timekeeping the previous day (this appeared to be a staff issue rather than a technical problem). The system is fully accessible to the mobility impaired. All platform faces have a substantial outstand of about 100mm plus a rubber moulded section about 50mm wide bolted to the face of them. Despite this and the fact under the safety case all trams have to stop at all platforms even when running out of service all tram doorways are fitted with sliding threshold plates on a pair of rotating arms. The trams appear to continue to run in service when these have failed at individual doorways. The leading corner of a number of the platform edge units appeared to have been struck heavily by road vehicles at suburban stops on Line B.

The reliability problems with the APS system have been identified as poor drainage (the design has been changed since the early days), water tightness, corrosion of power cables (due to acid attack) and the CA units themselves. The CA units are currently at design version ‘J’ though not all units presently in use have been upgraded yet. Some modifications are still outstanding and reliability problems are still being isolated and rectified on the original sections.

The safe switching of power supplies to each track section is controlled by the combination of an RF signal from the tram to the track, the detection of the loop formed by the presence of the tram’s collector shoe and a safety loop which links a number of adjacent CA units. Each CA unit is linked to the scada system. Substations are placed more or less every kilometre but the same spacing and the same power system design is maintained for either APS or OLE current collection.

Based on an interruption to service of 10 minutes or more, the reliability levels for the three lines during September were as follows:

Line A - 99.74%
Line B - 97.46% (EMI problem identified at one location)
Line C - 100.00%

Over the past 12 months the average has been 98.4% but Thierry Ficat thought that it had now improved considerably. The tram system is intensively used with frequencies down to 4 minutes in the peak and daily patronage at up to 180,000 compared with the prediction of 130,000.

Debris, Coke cans etc on the APS rail have been a problem and the driver on the first tram in the morning is responsible for checking that each section of track is clear.

Trams are limited to 50km/h when operating on APS because of the risk of leaving a live section exposed for a short period if travelling at a higher speed. Although Alstom’s contract calls for regeneration to be available with either mode of current collection this is not achieved with APS due to concerns about safety and Ficat didn’t seem to think that it would be without a major re-design.

There are a large number of road crossings on nominally segregated sections of tramway and long sections where the track in one direction is used by road traffic for servicing and access. The paving material used is predominantly blacktop outside the central area and stone flags or setts within it. Problems have been experienced at a number of shallow angled road crossings with heavy road vehicles breaking up the surfacing; it is likely that in these areas a concrete form of road construction will be adopted, despite resistance from the planners.

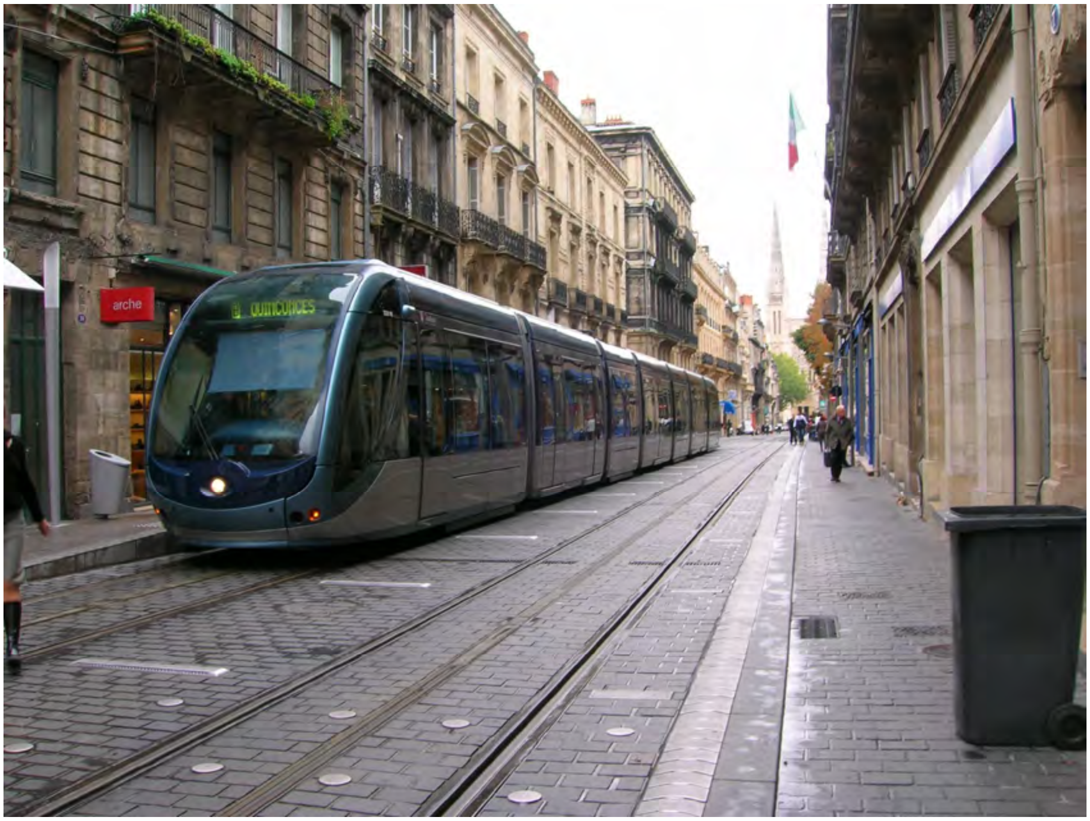
The APS rail is heavily polished by road traffic at busy road crossings. The twin contact strips on the top of the APS rail have only a nominal upstand of about 5mm; it remains to be seen how rapidly these will wear under constant road traffic or how difficult the process of rail replacement will prove to be.

Issues for Edinburgh

- Achieving reliable operation on a sustained long-term basis
- Obtaining UK safety certification, particularly in view of the different climatic conditions compared with Bordeaux and Marseilles including higher rainfall, snow, ice, salt and slush
- The low skid resistance of the relatively broad APS rail and the safety implications for road traffic of the internal camber required within the four-foot to promote drainage
- Keeping the rail clear of obstructions and debris
- Although visual intrusion is eliminated at “sky level”, the installation in the street is significantly more obtrusive than would otherwise be the case. This applies particularly within paved areas where otherwise only two tram rails would be visible
- The lack of a competitive market. There is only one supplier available and although Bordeaux are committed to buying their trams and track from the existing suppliers for the foreseeable future but are already conscious of the lack of competition. This would be a major problem for Edinburgh as the safety critical items are found both on the track and the trams: the two would have to be procured from a consortium able to supply and integrate both together with the necessary safety certification.
- The need for information on the long term performance of the APS track and its wearing elements under heavy road traffic

Actions

- Extract material on APS for use in Technology Review of Wire-free traction power systems
- Obtain further details from Alstom on traction batteries required for APS together with weight and cost
- Obtain copy of the Bordeaux PowerPoint presentation.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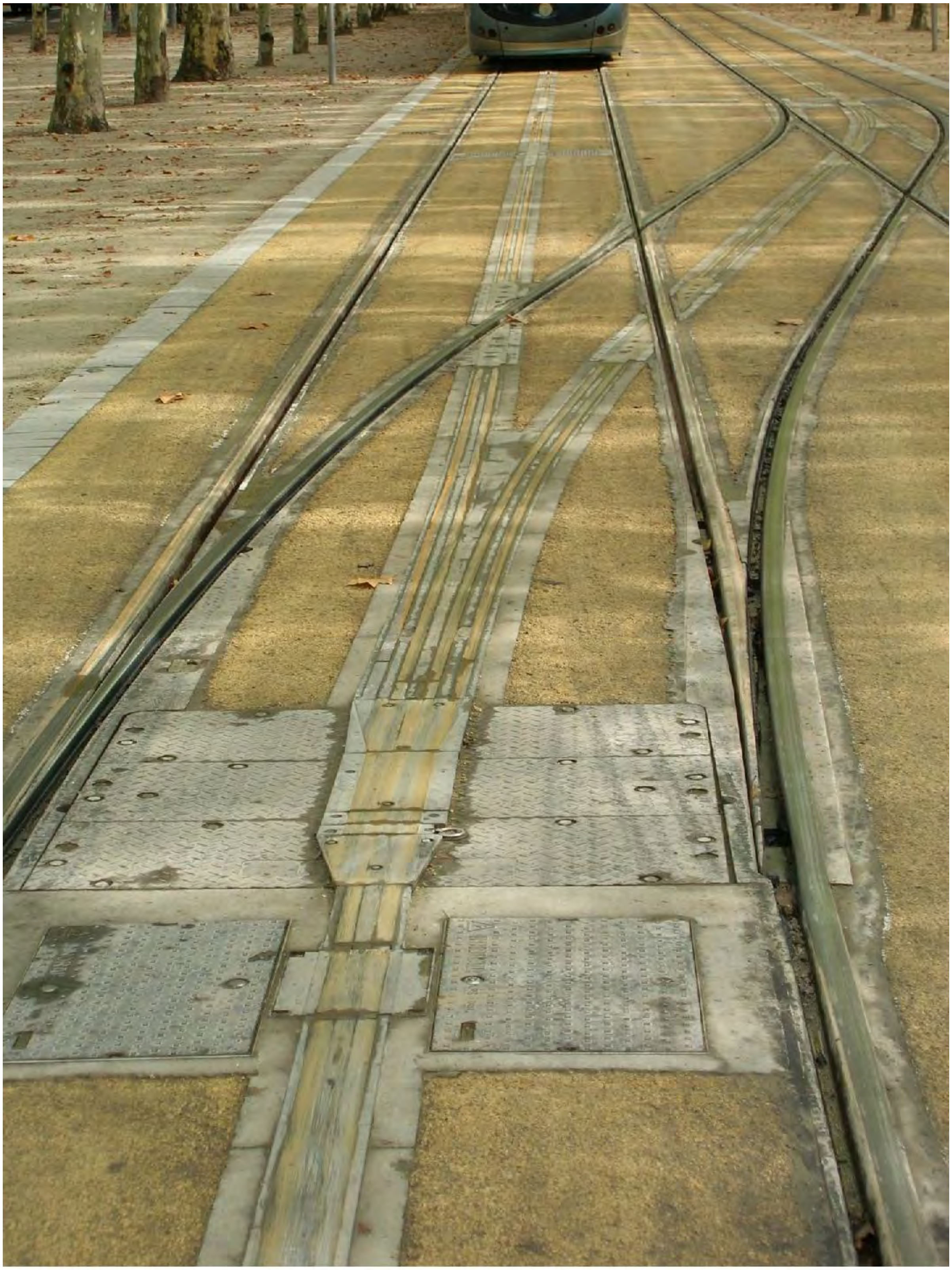

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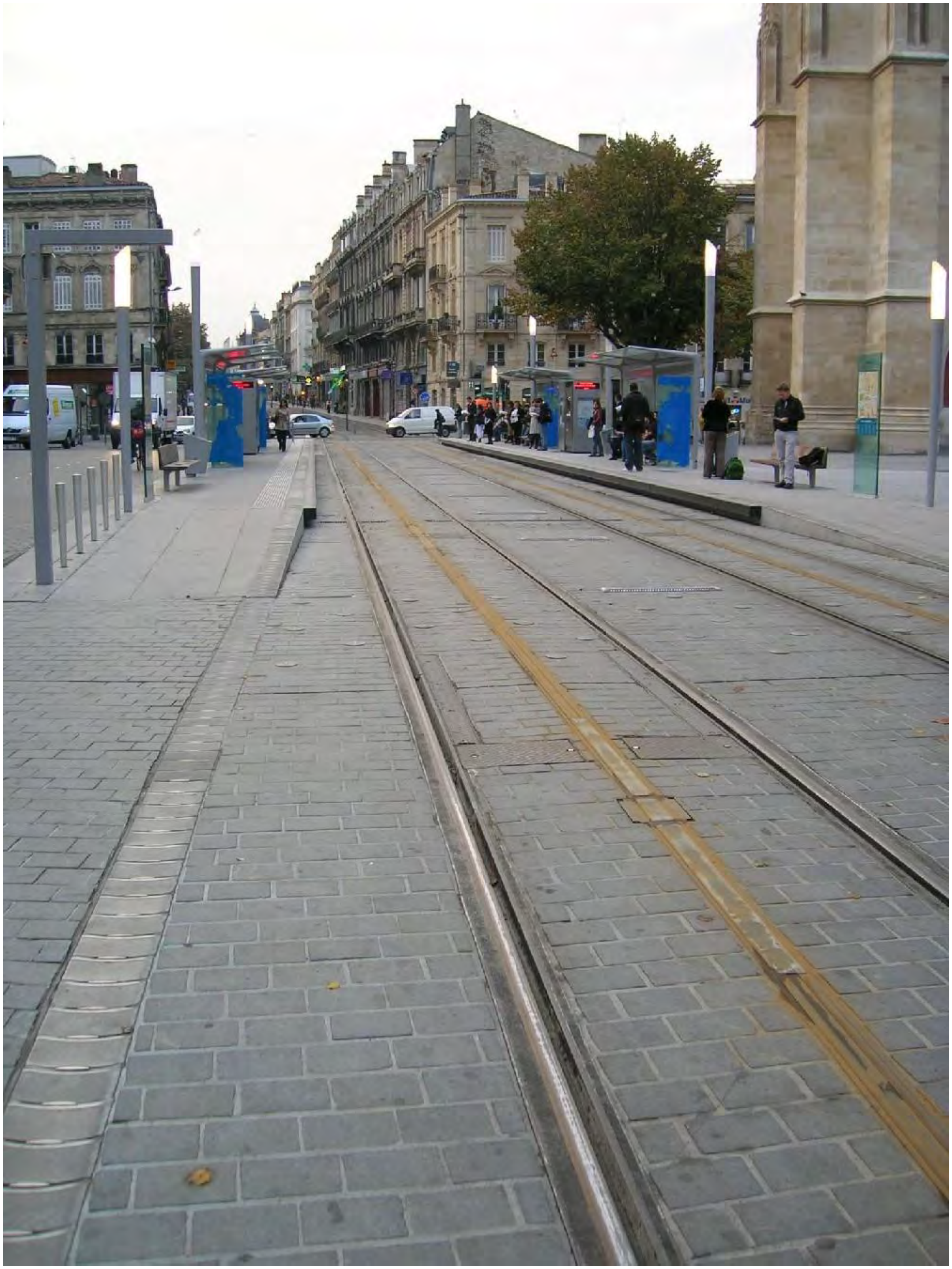

Bombardier PRIMOVE vehicles.

Alstom APS tram passing Cathedral of St Andre, Bordeaux. PHOTO: Shutterstock.com

No wires - Alstom APS tram passes Place de la Bourse, Bordeaux. PHOTO: Shutterstock.com

Trams without wires

28 Nov 2012 · **by** David Shirres · **in** Featured rail engineer Rail News, Light Rail · **4** Comments

For those working on heavy rail, the way streets absorb tram infrastructure to show only running rails is impressive indeed. Even more impressive is that some streets are now absorbing the tram's power supply as well, the result of a drive by the major tram manufacturers to make trams more attractive by eliminating the need for overhead wires.

This is actually a far from new idea as early trams collected current from ploughs in below-street conduits. These were connected to the tram through a slot in the centre of the tramway but were labour intensive, expensive to install, and vulnerable to items dropped in the slot. Blackpool has one of the world's earliest electrically powered tramways. When it opened in 1885, it was powered by a conduit system that was converted to an overhead supply 14 years later. The conduit didn't like Blackpool's sea and sand.

For modern trams, there are now various second-generation catenary-less systems of which ground level supplies are just one solution. Others include the latest energy storage technology and overhead top-up at stations. All are the fruits of a commitment to innovation by manufacturers to challenge the conventional idea that trams must be powered from an overhead catenary.

As these companies compete for their share of the worldwide expansion of light rail systems, they strive to make their products attractive to their customers, the city authorities. They, in turn, need to convince the people of the city. Eliminating overhead wires removes visual intrusion which is a critical factor in historic cities. Moreover, utility work for its poles or fixings on people's houses can also result in objections. Although public opinion is a significant issue, it will also be seen that energy efficiency and lower infrastructure costs also provide good reasons not to erect tram wires.

Ground Force – French-style

Alstom's Alimoitere Par le Sol (APS) was the first second-generation catenary-less tram system. It began operation in Bordeaux, a UNESCO world heritage site, in 2003. Up until 1958, Bordeaux's trams used the conduit system, and it had been assumed that the new trams would operate similarly. However it was decided that, as the old conduit system was not suitable, the new trams would have overhead wires. The resultant protest from both the public and the French Ministry of Culture resulted in the development of the APS system which is used for twelve kilometres of Bordeaux's 44 kilometre tram network.

Alstom's APS consists of a conduit, flush with the ground, on top of which are 8 metre long contact strips alternating with 3 metre long insulated segments. Inside this conduit are the supply cables and an antenna. There is a power supply box adjacent to every other insulated segment that feeds the adjacent contact strips. These are energised only when the antenna detects that the tram is wholly above the contact strip. To maximise power transfer time, contact shoes are in the centre of the tram.

The APS system had some initial teething problems. Like Blackpool in 1885, one of its initial problems was seepage and moisture. This required electrical housings and insulators to be redesigned. Now that these issues have been resolved, the Bordeaux tram system is 99.8% reliable and the city is now satisfied that it has a robust, reliable system.

Alstom claim that the installation cost of APS is comparable with that of tram catenary wire as the APS conduit requires minimal civil engineering work, being only marginally deeper than the slab track. In contrast, particularly in complex city areas, a catenary may require utility work for its masts and significant legal costs may arise if it has to be fixed to adjacent buildings.

A potential cost issue is maintenance of switchgear, with power supply switch boxes embedded in the street every 22 metres. Alstom advise that these are modular units which can quickly be replaced. Maintenance is by programmed replacement over a long period of time, enabling the units to be overhauled at service centres.

APS is also now in use as part of the Angers, Reims and Orléans tram systems. Outside France, work has started on APS tramways in Brasilia and Dubai which are planned to open in 2014. In Dubai the trams will have brushes to keep the contact strips clear of sand.

The Alstom APS system is not the only ground-contact system on the market. In Italy, Anasaldo have developed a modern version of the original conduit system. This has flush conductor and return rails in the centre of the tramway. In the troughing beneath is a flexible ferromagnetic belt which is lifted by magnets on the tram to energise the conductor rail. As the running rails do not carry return current, the system can be used for buses. The first use of this system will be on a section of Napoli's tramway at the end of this year.

Looped power

Also at ground level, but invisible, Bombardier's PRIMOVE system is entirely hidden by the city's streets. PRIMOVE uses buried inductive loops between the tracks to transmit power to trams. These loops need to be covered by a 40mm layer of non-conductive material such as resin, asphalt base or non-reinforced concrete which may need to be carefully installed or it might be vulnerable to heavy traffic.

Each looped cable segment is eight metres long and transmits 200kw. It is fed by an inverter which transforms 750 volt DC into 200 kHz AC. This system has transmission efficiencies of between 90% and 95%, which Bombardier advises is only 2% less than contact systems.

Like APS, PRIMOVE is only switched on when the tram is above it by a maintenance-free solid-state unit. Power transmission loops are generally located at stations and gradients as required by the tram network. The loops fit above sleepers and so involve no additional civil engineering costs.

Unlike APS, it does not continuously power the tram so energy storage is an essential aspect of the PRIMOVE system. Bombardier's MITRAC Energy Saver uses super-capacitors and was originally designed to store energy from regenerative braking. Trials have shown savings of up to 30% of traction energy.

The PRIMOVE concept has been successfully demonstrated in Augsburg where Bombardier low-floor trams have been using it on an 800 metre spur line to the city's exhibition centre since 2010. Further testing has been done at Bombardier's e-mobility hub in Mannheim which opened in September 2011 and which has also tested PRIMOVE buses, minivans and cars from 3.6kW to 200 kW.

Trolley buses without wires

As PRIMOVE vehicles are not limited to rail or a fixed route, its equipment can easily be fitted to road vehicles. A battery powered bus running, say, 250 kilometres per day requires a six or seven ton battery. Bombardier have calculated that if PRIMOVE is used for charging, only a one ton battery is required and that a single charge point, located at a central part of the bus network could, typically, provide 20 charges a day with no effect on the bus service. Charging buses in this way also extends battery life. Thus for minimal infrastructure investment, it could enable a city to operate a fleet of electric buses with the same performance as diesel buses.

Although PRIMOVE buses would seem to offer huge environmental and cost benefits, these have yet to be demonstrated in practice. To demonstrate this concept, a pilot programme of PRIMOVE bus operation is planned for five cities in 2013 – Bruges and Lommel in Belgium and

Augsburg, Braunschweig and Berlin in Germany. These pilots involve various types of buses of up to 200 kW and 18 metres long. In Braunschweig, the German Ministry of Transport has given a grant of €2.9 million for the PRIMOVE bus pilot on a 12 kilometre section of its bus network to become operational autumn 2013.

PRIMOVE's greatest potential impact is its use in cars. To test this concept, the Lommel pilot bus scheme includes tests with a 22kW Volvo C30 car. Until now, battery size, range and time-to-charge have been insuperable constraints to the widespread introduction of electric cars. By removing these constraints, PRIMOVE has the potential to change motoring as we know it.

The storage solution

Siemens have been building trams since they provided the world with its first electric tram, powered from overhead wires in the Berlin suburb of Lichterfelde in May 1881. It's therefore no surprise that they also offer trams without wires using their Sitras HES (Hybrid Energy Storage). This system has been in use in Lisbon, Portugal since November 2008 and has been selected by Qatar for its Doha tramway which will be operational in 2015 as part of the preparations for the 2022 World Cup.

HES is a modular system that can either be built into new vehicles or installed in existing trams, enabling them to run for distances up to 2.5 km without wires. It comprises two 820kg roof mounted units: a nickel-metal hydride cell (NiMH) battery and an MES (Mobile Energy Storage) unit using double-layer "super capacitors". Batteries have a higher energy density than super-capacitors but take longer to charge. In the HES unit the respective stored energy of batteries and super-capacitors is 18 kWh and 0.85 kWh whilst the respective power output is 105 kW and 288 kW. For this reason, HES uses super-capacitors for acceleration and batteries for steady speed. Another advantage of such storage systems is that they eliminate power spikes when several trams accelerate at the same time.

Unlike APS or PRIMOVE, Siemens HES trams require an overhead supply. This may be conventional overhead wires on part of the network or a Sitras LCU (Local Charging Unit). The LCU is a short length of overhead conductor rail placed at stations or other stops that can deliver a 1,000 amp charging current during a typical 20-second station dwell time. HES is also charged from regenerative braking, which Siemens claim can reduce energy consumption by 30%.

A similar system has been developed by Spanish manufacturer CAF. This uses its ACR freeDRIVE which, when used in conjuction with the ACR evoDRIVE, developed to save energy from regenerative braking, offers up to 1.4 kilometres of catenary-free operation. It has been used on a 1.6 kilometre section of Seville's tramway since 2010 and is also in use in the Spanish cities of Zaragoza and Granada .

In Nice, Alstom have fitted their Citadis trams with extra NiMH batteries for 500 metres catenary-free operation across two historic squares. On the Paris T3 tramline, a Citadis tram has been fitted with a bank of 48 supercapacitors to simulate catenary-free running.

Alstom is also trialling flywheel storage on a tram in Rotterdam. This is roof-mounted and runs in a vacuum at speeds around 20,000 rpm providing a net energy storage of 4kWh and 325 kW peak power. It will be interesting to see if a modern flywheel can compete with the increasing use of super-capacitors.

And the winner is….

With UNIFE predicting a 9.3% increase in the world's urban rolling stock market over the next 5 years, tram manufacturers are doing all they can to increase their market share and catenary-less trams are one way to do this. However, the technology is quite novel. The oldest system, Alstom's APS, is less than 10 years old and has now proved itself in service, although initially it had significant teething problems which have been resolved. Other systems offer great potential but are quite new and have yet to be subject to the intensive use needed to demonstrate their reliability.

All these systems have their pros and cons and what is best for one city will not be for another. For these reasons it would be wrong to name the best system. However, with its potential to increase the number of electric vehicles on the road, PRIMOVE offers an interesting potential environmental benefit.

The real winners are cities that now do not have to erect tram wires in their city centres. This not only preserves historic centres, but, in complex city centres, could reduce construction and utility costs. However, the case for catenary-less trams outside the city centre is less clear.

Another surprising winner, albeit in the long term, may be the motorist for whom fuel pumps could be a thing of the past as they drive PRIMOVE electric cars with the performance and range of today's cars. Transferring technology from rail to road in this way shows just how innovative rolling stock manufacturers have become. There are, no doubt a lot more innovations to come.

Feasibility of Alternative Power Supply Systems for the LUAS BXD

20 April 2012

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1. INTRODUCTION

1.1 Purpose of the document

An Bord Pleanala as part of its deliberations to determine whether the LUAS City Broombridge (BXD) project should be granted consent to proceed, has employed SYSTRA in order to examine the feasibility of employing an alternative to the Overhead Contact System (OCS)[1].

An alternative traction system is envisaged for portions of the BXD line that would run in visually sensitive areas of the city centre of Dublin: from St. Stephen's Green to the north end of O'Connell Street (about 1.7 km). Alternatives have been examined in terms of technical feasibility. Additionally, we have provided elements regarding industrial availability and cost. The terms of reference drawn up by An Bord Pleanála are provided in Appendix 1.

The objective of this work is to provide the Board with further information, clarification and assistance on the subject - independent of the project developer - to facilitate its decision regarding employment of an alternative system to OCS on the LUAS BXD.

1.2 SYSTRA

SYSTRA is a world-leading engineering consultancy specialising in urban and rail transport. We work on all stages of transportation projects, from master plans and feasibility studies up to project execution and technical assistance for operations and maintenance. SYSTRA is involved in transport projects around the world, and boasts numerous references working with light rail systems.

SYSTRA has been involved in the implementation of alternative power sources for light rail systems in Dubai, Qatar, Rheims and Bordeaux.

1.3 Evaluation criteria

In this document we evaluate and compare the available alternative technologies, and we identify to what extent they would be applicable to the LUAS BXD requirements. The following points are explored.

System reliability

The reliability of each system is examined, taking into account the specific conditions of the BXD line, in particular shared running and climate conditions.

Suitability (and safety) for the proposed level of shared running

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[1] OCS can also be referred to as "overhead line" or "catenary". We use both the terms "OCS" and "catenary" throughout this document.

We will evaluate the suitability of each system for the proposed level of shared running with cars, buses, bicycles, etc.

Ability to cope with adverse weather conditions

Specific attention is paid to the ability of systems to deal with adverse weather conditions such as heavy rain and snow.

Energy considerations

Energy considerations are examined with regards to the technical characteristics of each possible solution.

Retrofitting on existing fleets of trams

We evaluate the technical possibility of retrofitting existing fleets of trams.

Capital and operational costs

We estimate capital and operational costs associated with the alternative system(s), as compared to OCS.

Industrial capacity

We examine industrial capacity for delivery of each possible solution. In addition, attention is paid to the constraints that the choice of each solution will impose for the future: dependence on a single provider or not, degree of deployment of the system in other LR networks...

Prior deployment

An Bord Pleanála has suggested that the main focus should be for a system that has already been proven on an existing in-service tramway.

1.4 Reference documents

As part of its consideration, SYSTRA has referenced a suite of selected documents, drawings and information including EIS documents and oral hearing submissions (see full list attached as Appendix 2 to this report) provided by An Bord Pleanála.

1.5 Visit on site

In addition to the above documents, SYSTRA representatives visited the offices and met with representatives of An Bord Pleanála, visited the LUAS depot at Sandyford (accompanied by a representative of An Bord Pleanála) and inspected the subject area of the report and existing LUAS running arrangements during a visit to Dublin on the 7th and 8th March 2012.

2. KEY FEATURES OF THE SECTION OF THE BXD LINE UNDER STUDY

In order to be able to assess the technical feasibility of an OCS-free power supply in the section of the BXD line between St. Stephen’s Green and the north end of O’Connell Street, the key features of this section must be understood and analyzed, especially those which may have an impact on the potential technical solution.

The compliance of the various technical solutions to the requirements identified here is assessed in chapter 4 of the current document.

2.1 Gradient and distance between stations

Gradient and distance between stations are of particular concern for some OCS-free power supply systems.

In the case of the section under study, the maximum distance between two adjacent stations is about 480 m (between the Dawson and the Westmoreland stations), and the maximum gradient is less than 1.5% (between St. Stephen’s Green and Dawson).

Both values are low enough that they will not pose particular problems for any of the OCS-free power supply solutions evaluated.

2.2 Running environment

Two key characteristics of the BXD running environment between St. Stephen’s Green and the north end of O’Connell Street are the following:

- Along most of the section, the tramway shares its track bed with road traffic.
- Some of the alignment sections are narrow (from façade to façade); as such, bulky equipment will need to be accommodated in underground technical rooms.

These two features lead us to identify two requirements:

- Any equipment installed in the track bed must be able to withstand heavy road traffic, without adding potential hazard to road users.
- Space requirements for equipment to be installed along the line should be kept as low as possible.

Example of section with both heavy traffic and tight space for the new line

2.3 Impact of road traffic on tramway operation

The sharing of the track with road traffic along most of the section under scrutiny has an obvious potential impact on tramway operation, as trams risk to get stuck in traffic.

In addition to that, we learnt from RPA during our visit in Dublin that the level of priority given to trams at intersections is decided by the city council. Current policy is to provide limited priority to trams during peak hours in order to avoid blocking road traffic running perpendicular to the tram route.

These two factors mean that tram operation is likely to be impacted upon by traffic, such that trams will have to stop and start several times between two stations.

Therefore, the OCS-free power supply solution must be able to handle a situation in which trams may be forced to stop and start multiple times between any two stations, without risk that trams may be left stranded without power in the middle of dense traffic.

3. OVERVIEW OF THE CATENARY-FREE SYSTEMS AVAILABLE ON THE MARKET

The purpose of this section is to provide a high-level understanding of the various solutions currently proposed by tramway providers to ensure the supply of power without an overhead catenary.

These systems can be classified in two main different categories:

- Systems based on on-board energy storage
- Systems based on a continuous power supply from the track bed

For each of these concepts, various solutions are proposed by rolling stock manufacturers. The following paragraphs provide an overview of the main technical and operational features of the available systems.

3.1 Systems based on on-board energy storage

The three following solutions all rely on an on-board energy storage device which supplies the tram while it runs on sections without an overhead catenary.

3.1.1 CAF Super Capacitor system

3.1.1.1 Operating principle

The system proposed by CAF is based on a Rapid Charge Accumulator, branded ACR by CAF, which stores energy in super capacitors[2] to feed the tram.

There are two situations in which the ACR is charged:

- A partial charge when regenerative braking is used
- A complete charge when the tram is stopped at a station that precedes an OCS-free section

Stations are equipped with a short section of overhead rigid catenary, and the tram raises its pantograph when it stops in stations.

The power stored in the ACR is used in two situations:

- On the section fitted with OCS: during the acceleration phase to reduce the current peak drained from the OCS

---

[2] Super capacitors are particularly high-bandwidth energy storage devices. They can store large amounts of energy very quickly and can also release energy very quickly. A battery, on the other hand, takes more time to store energy and releases it more slowly.

- On the OCS-free section: to feed the train during its whole trip until the next station

3.1.1.2 Key features

The super capacitors (also called “super caps”) used to store energy are the key component of ACR.

The benefit of using super caps is to make it possible to transfer a great deal of power in a short period of time. The super capacitors are charged during the dwell time which should last between 20 and 30 seconds, depending on the length and gradient between stations.

3.1.1.3 Life expectancy

The super capacitors are under high stress because they go through permanent charge-discharge cycles.

They require a temperature control system (dedicated air conditioning unit) in order to avoid operation under high temperature that would be detrimental to their life expectancy.

Manufacturers indicate that their life expectancy is estimated to be from 7 to 10 years, depending on the actual mission profile of the OCS-free sections.

3.1.1.4 Use of batteries

In order to cope with some particular configurations (exceptional distance between two stations, trams equipped with powerful air conditioning or heating), the super capacitors may be associated with batteries.

The batteries contain more energy than super capacitors, but the maximum current acceptable at a time is much lower, so the charge/discharge cycle takes place on a longer time scale. The batteries are charged when the trams run on sections equipped with OCS, and slowly discharged on the OCS-free sections.

3.1.2 Siemens Super Capacitor system Sitras MES / Sitras HES

3.1.2.1 Operating principles

The operating principles of the Siemens solution are identical to those described above for the CAF solution, i.e. the tram is powered by on-board energy storage device(s) when running on OCS-free sections.

3.1.2.2 Specificity of Sitras MES / Sitras HES

Siemens proposes in its standard solution a mix of batteries and super capacitors.

The batteries supply the constant background load, whereas the super capacitors supply the power peaks and store the energy produced by regenerative braking.

3.1.3 On-board battery by Alstom

3.1.3.1 Operating principles

The solution proposed by Alstom and Saft for the tramway in Nice, France, relies on on-board energy storage as well.

In this case, energy is stored in Nickel Metal Hydrure (Ni-MH) batteries when the tram runs on sections equipped with OCS, and this energy is used on OCS-free sections.

3.1.3.2 Key features

The distance that can be covered while running on an OCS-free section with this solution depends on the battery capacity and the length of the preceding OCS section where the batteries are charged beforehand.

The solution implemented in Nice covers two sections for a total length of about 900 m.

On these sections located in the historical centre of the city, the tram crosses pedestrian areas at low speed.

It has to be noted that operation on batteries reduces the achievable rate of acceleration, the maximum speed and possibly the commercial speed.

3.2 Systems based on a continuous power supply

3.2.1 APS by Alstom

3.2.1.1 Operating principles

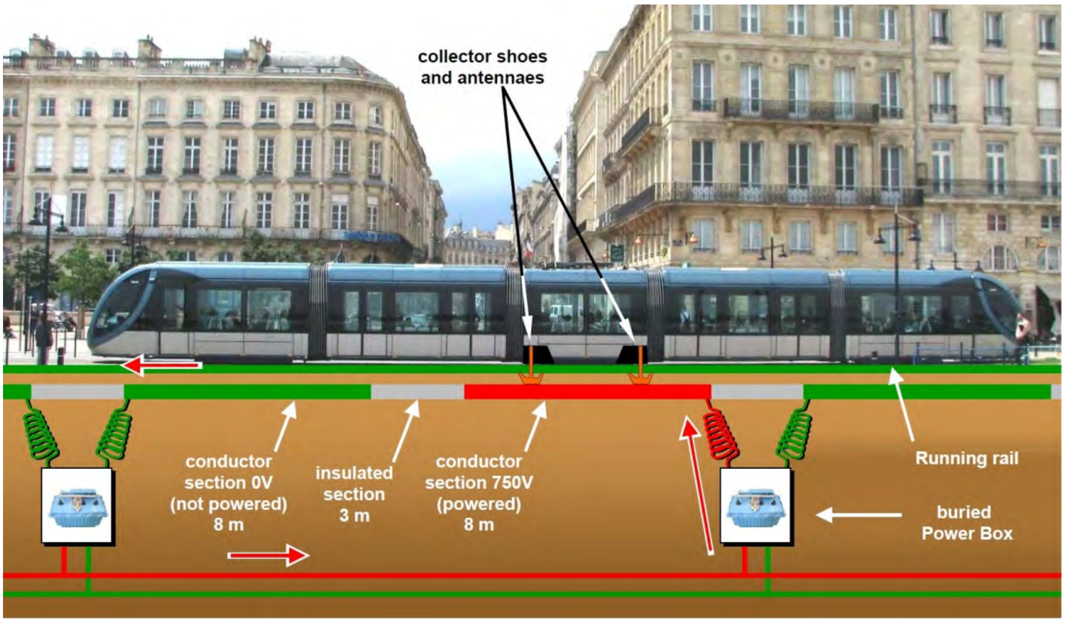
Alstom's APS system is based on traction power supplied to the vehicle by a power rail located between the running rails. The rolling stock uses a current collector shoe to obtain power via physical contact between the collector shoe and the track-embedded power supply rail.

The power supply rail is divided into 8 m long segments separated by 3 m long insulation segments.

The rail is fed with 750 V DC from "power boxes" embedded in the track.

Segments of power supply rail are only activated when they are completely covered by a tram vehicle.

This principle ensures a live rail is never accessible to pedestrians. Loops embedded in the track bed detect the presence of a vehicle via a coded radio signal emitted by the trams. This energy-distribution principle through segmentation is illustrated in the figure below.


collector shoes and antennaes
conductor section 0V (not powered) 8 m
insulated section 3 m
conductor section 750V (powered) 8 m
Running rail
buried Power Box

When there is no vehicle over a given section, the rail is electrically connected to the return-current circuit (0 V) to avoid any unwanted powering up of the APS rail.

APS allows for catenary-free sections of any length, or even on the whole line.

Transitions between APS sections and catenary-equipped sections require that the tram come to a full stop. Practically, the transition is made within stations so that dwell time can be taken advantage of in order to minimise the impact of the transition time.

3.2.1.2 Specific features

The maximum operating speed on APS sections is 50 km/h, while an Alstom Citadis vehicle can operate at 70 km/h with overhead catenary.

In order to mitigate local failure of the system, the vehicles are equipped with batteries. These batteries enable trams to cross failed sections of up to 50 meters.

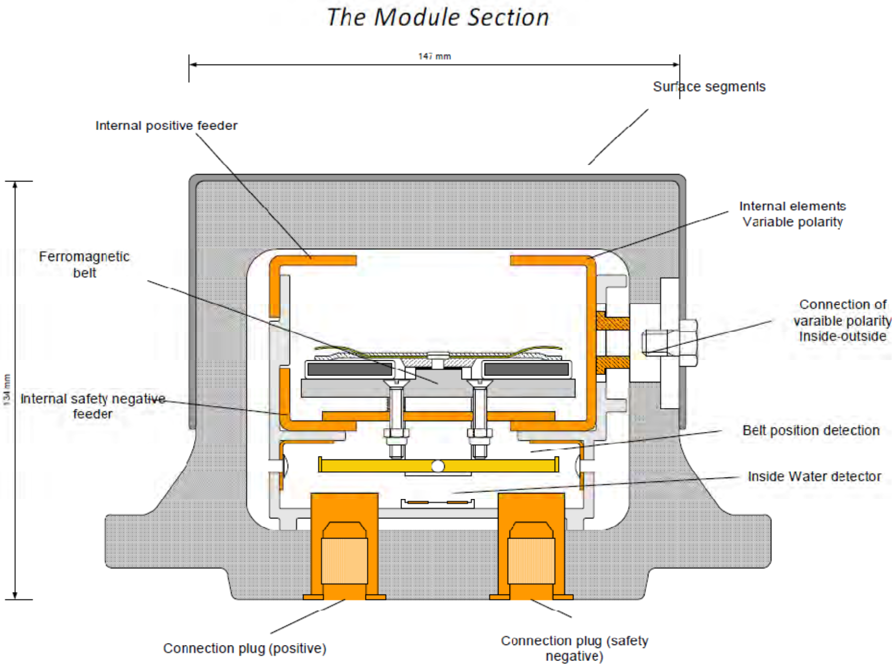
3.2.2 Tramwave by Ansaldo

3.2.2.1 Operating principle of the Tramwave system

The Tramwave system provides trams with a continuous 750 DC power supply thanks to modules embedded in the track between the running rails.

The power is collected through a collector shoe. For safety reasons, only the modules located beneath the tramway collector shoe are powered up, so the hot part is never accessible to the pedestrians.

The powering up of the sections under the collector shoe is ensured by a relatively simple electromechanical solution: the collector shoe contains a powerful permanent magnet which lifts a metallic belt contained in the track-embedded module. When this belt is positioned in the upward position, contact is ensured between the 750 V DC feeder running along the Tramwave module ("internal positive feeder" on the upper left of the drawing below) and the "internal elements variable polarity" (on the upper right of the drawing) and the metallic surface segment on the top of the module. The part labelled as "internal elements variable polarity" is permanently connected to the "surface segment" (top of the drawing), so the "surface segment" is brought to 750 V DC potential.



Tramwave power rail cross section (© Ansaldo)

When the belt is positioned in the downward position, the part labelled "Internal elements variable polarity" is connected to the "Internal safety negative feeder" through the lower part of the belt and thus the metallic surface segment is connected to the negative feeder. The negative feeder is connected to the 0 V pole of the substation (as well as the running rail).

The safety of the Tramwave system is based on the fail safe principle: in the event the metallic belt remains stuck in the upward position after the collector shoe has left the zone, the lower part of the belt will fall due to its own weight and connect the metallic surface segment to the internal safety negative feeder. At this point, there is a short circuit between the positive and the negative feeder, leading the high speed circuit breaker to trip immediately.

The Tramwave modules are supervised from the operating control centre (OCC): the operator can monitor the electrical status of each section.

In addition, the presence of water inside the module is detected by a dedicated captor and the corresponding alarm sent to the OCC.

An on-board battery can carry the tram along a section in which the track bed modules malfunction.

On a recent bid, Ansaldo proposed on-board super capacitors to improve energetic efficiency. These super capacitors have a much lower capacity than those proposed on CAF and Siemens solution because they are not the primary source of power.

3.2.2.2 *Operation of the collector shoe*

The collector shoe contains the permanent magnets which lift the belt in the platform-embedded module.

For safety reasons, these magnets are made up of several magnets and are arranged in a way such that they repulse each other (S-N N-S S-N), but they are kept together by the structure of the collector shoe. In the event of a breakage of the collector shoe, the magnets will repulse each other. Each magnet taken individually is not strong enough to lift the belt, so a broken collector shoe cannot lead to a powered module by leaving loose magnets.

The collector shoe is maintained in the upward position by a spring. In order to lower it, a hydraulic system has to compensate the force of the spring.

The force of the spring is greater than the force of the magnet, so any failure of the hydraulic system would release the collector shoe to the upward position, thus setting the rail to 0 V.

3.2.3 *Primove by Bombardier*

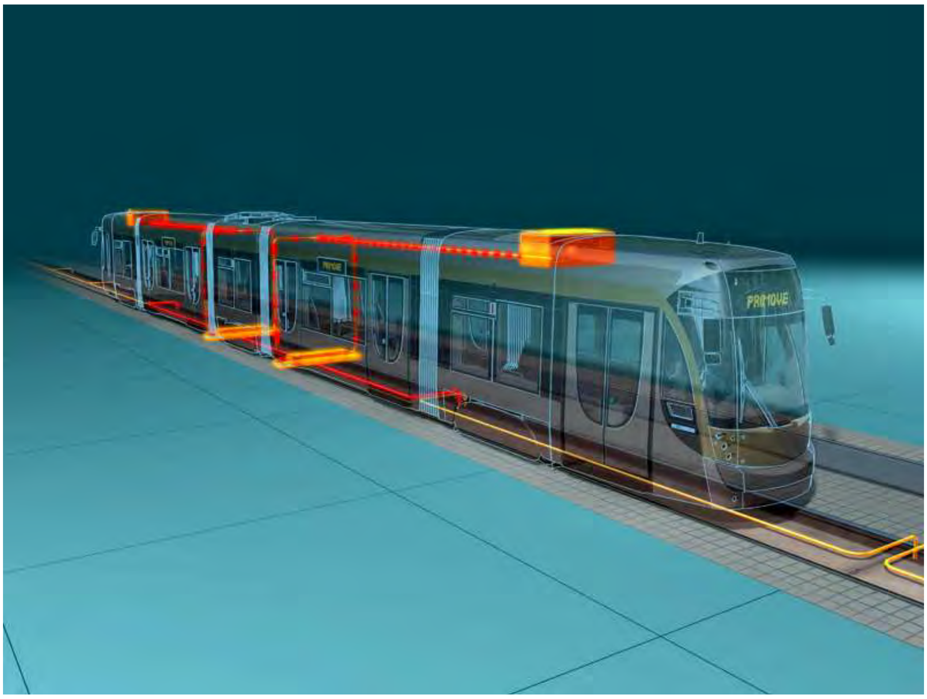
3.2.3.1 *Operating principle*

Bombardier’s Primove solution provides continuous power to the tram thanks to induction loops embedded in the trackbed and coils installed under the frame of the tram.

Power is transmitted, without any physical contact, through the electromagnetic flux produced by the embedded loop.

The coils embedded in the track bed are powered on only when the tram is running over them to avoid unnecessary electromagnetic emission.

The tram is detected via the coded radio signals that it emits and which are received by the trackside equipment.



Bombardier’s Primove system (© Bombardier Transportation)

3.2.3.2 Specific features

Although Bombardier has not revealed extensive technical details on the Primove solution, some specific technical features are known.

The amount of power the induction loops are able to transfer is less than the power transmitted with an OCS, so the Primove solution cannot deliver the power peak required to maintain constant acceleration of the tram above 20 km/h. In order to solve that problem, the tram is equipped with super capacitors which provide the required boost needed during the second part of the acceleration phase.

These super capacitors, presented as an improvement of the basic Primove solution, are in fact a mandatory feature.

The loops embedded in the track bed must be covered by a plate made of a material which does not contain any metal because metal is conductive and would shield the electromagnetic flux.

4. ANALYSIS OF FITNESS FOR PURPOSE

In this chapter we evaluate the fitness for purpose of each of the technological solutions described above. The evaluation criteria are defined in function of both the constraints linked to the BXD extension and the brief provided by An Bord Pleanála (principally reliability) and reproduced in Appendix 1.

The analysis begins, for each technology, with the constraint and criteria of the highest importance to proceed further with criteria of lesser importance. In the event one of the technologies does not comply with one of the mandatory requirements, making it unsuitable for the BXD line, the analysis is not be pursued further with the criteria of lesser importance.

4.1 Suitability of CAF super capacitor system

4.1.1 Fitness for shared running

4.1.1.1 Mechanical aspects

This solution based on super capacitors does not require the installation of any specific equipment in the track bed along the catenary-free section.

In other words, the track bed will be identical to the track bed implemented along the section fitted with catenary, so the super cap solution is compatible with shared running from a mechanical point of view.

4.1.1.2 Running in congested traffic

Shared running along the busiest streets of the city centre means a potential risk of having a tram stuck in traffic, requiring several stops and starts between two stations.

The super cap solution is based on the principle that the tram carries its own on-board power supply. This supply is sized to be able to cover the longest distance between stations and includes a margin to be able to face an unscheduled stop between two stations.

In congested traffic, the maximum number of unscheduled stops between stations cannot be predicted; neither can their duration (when the tram is stopped, ventilation, lighting, and other ancillary equipment keep on draining down the supply).

It seems unlikely that the on-board supply could be sized such as to ***guarantee*** that there would be no risk of trams running out of power (and thus getting stuck) between stations.

Moreover, sizing the super cap supply such that it could handle some predefined scenario of congested traffic would lead to a significant increase in both its size and weight.

Since a train which has run out of power has no possibility of moving without being rescued by another tram or vehicle, such an event would have a significant impact both on tram operation and road traffic.

4.1.2 Conclusion

The combination of shared running (and thus the likelihood of having to handle congestion) and a super cap on-board power supply system leads to an unquantifiable risk of having trains stranded in the middle of the city centre.

This major drawback leads us to conclude that, based on currently available information, the super cap solution is not suitable for the BXD line.

4.2 Suitability of Siemens super capacitor and battery system

From a functional and technical point of view, the solution proposed by Siemens is very similar to the CAF solution, so the arguments discussed above will be quickly summarised below.

4.2.1 Fitness for shared running

4.2.1.1 Mechanical aspects

The solution based on a super capacitor does not require the installation of any specific equipment in the track bed along the catenary-free section, so the track bed will be identical to the one implemented on sections fitted with OCS.

4.2.1.2 Running in congested traffic

The energy stored in the super capacitors and batteries is limited, and – given the shared running that is planned for this section of the BXD line – it cannot be sized to cope with all possible scenarios in terms of unscheduled stops and starts.

4.2.2 Conclusion

The combination of shared running (and thus the likelihood of having to handle congestion) and a super cap on-board power supply system leads to an unquantifiable risk of having trains stranded in the middle of the city centre.

This major drawback leads us to conclude that, based on currently available information, the super cap / battery solution is not suitable for the BXD line.

4.3 Suitability of Alstom battery system

4.3.1 Fitness of shared running

4.3.1.1 Mechanical aspects

The solution based on batteries does not require the installation of any specific equipment in the track bed along the catenary free section.

As already mentioned for the super capacitor based solution, the track bed will be identical to the track bed implemented along the section fitted with catenary, so the super cap solution is compatible with shared running from a mechanical point of view.

4.3.1.2 Running in congested traffic

The battery solution has two major drawbacks when it has to run in congested traffic:

- The quantity of available energy is limited, and therefore so is the number of unscheduled stops and starts that the tram can withstand between two stations.
- The maximum current which can be delivered by the batteries is lower than the current delivered by the OCS or super caps; thus the rate of acceleration that the tram can achieve is limited.

4.3.2 Level of deployment

Alstom has deployed its battery solution only in Nice.

4.3.3 Conclusion

The Alstom solution based on batteries is not designed for shared running, and would present a high risk of having trams stranded between two stations after multiple unscheduled stops.

Thus, at the time of this writing, we consider that the Alstom battery solution is not suitable for the BXD application.

4.4 Suitability of Bombardier Primove System

4.4.1 Fitness of shared running

4.4.1.1 Mechanical aspects

The Primove system requires the installation of embedded electrical loops between the running rails.

These loops shall be covered by a 40 mm layer of nonconductive material such as resin, asphalt base course or non-reinforced concrete.

Bombardier has not provided information regarding the long-term resistance of this arrangement under road traffic.

Moreover, Bombardier does propose that the Primove track-embedded equipment not be implanted in intersections.

These aspects lead us to consider that there are currently no satisfactory technical solutions available to meet the requirement related to heavy road traffic running over the Primove embedded loop.

4.4.1.2 Running in congested traffic

The Primove system provides a continuous power supply, which makes it possible for trams to stop and start as many times as necessary, as long as they stop over induction loops.

According to Bombardier, at low speeds (below 18 km/h), the acceleration performance supplied by Primove is identical to that provided by an OCS; thus congested traffic and repeated stops and starts are not a concern.

4.4.2 Level of deployment

At this time, the Primove system is not implemented in commercial service.

In addition to the Bautzen test track installed in Bombardier premises, an 800 m long pilot section has been installed and tested in Augsburg, Germany.

This pilot section did not carry any passenger and was segregated from road traffic and protected by fences.

4.4.3 Conclusion

The Primove System is able to face congested traffic by withstanding frequent stops and starts, but, for the moment, in its current design, it does not appear to be able to withstand the load associated with shared running, as foreseen on the BXD line.

Moreover, although the Primove System has been proposed by Bombardier in some of its bids, it cannot be considered as a proven in use system.

For these reasons, we consider that, at the time of this writing, the Primove solution is not suitable for the BXD line.

4.5 Suitability of Alstom APS system

4.5.1 Fitness for shared running

4.5.1.1 Mechanical aspects

The APS solution requires the installation of a power rail between the running rails, embedded in the track bed.

In the BXD context, the power rail must be able to withstand continuous road traffic for years, without damage.

On French projects, APS is mainly installed on segregated running sections, except for road intersections where road traffic crosses the rail.

As part of its certification process, the first version of the APS system went through an endurance test to simulate the effect of urban traffic (over 700,000 cycles with 7-ton pressure wheels).

View of the endurance test plant (© Innorail)

Despite this test and certification process, the first version of APS installed in Bordeaux in 2003 suffered damage at road intersections. It is worth mentioning that in this previous design, the APS rail was directly embedded in asphalt.

Following this experience, Alstom revised its design to embed the APS rail in a concrete plinth to increase its resistance to road traffic. This improvement ended up being satisfactory in Bordeaux.

The latest design of APS (APS 2) now includes a reinforced power rail, still embedded in a concrete plinth. Alstom claims that it can withstand 13.5 ton axle loads.

For Dubai, Alstom's design is foreseen to withstand road crossings with more than 100 buses a day.

4.5.1.2 Running in congested traffic

The APS power rail continuously provides the same amount of power as an overhead catenary, so running in congested traffic is not a concern for a tram fed by APS.

4.5.2 Resistance to weather conditions

4.5.2.1 Flooding

The APS power rail, like any power rail, cannot operate when it is covered by water, because such a situation would lead to current leak when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit.

Flooding of the track bed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

Regarding the protection of the embedded power box, the latest APS design is based on an IP 68 rated box, which means, according to standard EN 60529, it can remain immersed in 1 metre of water for 15 days.

4.5.2.2 Snow and ice

On December 28th, 2006, relatively light snow falls in Bordeaux lead to the interruption of tram service on sections equipped with APS.

The layer of snow between the collector shoe and the power rail prevented proper contact and thus the feeding of the tram.

In the morning of December 29th, 2006, the snow melted during the day and then froze during the night, forming a layer of ice on the power rail, making it even more difficult for the maintenance teams to clean it. On January 24, 2007, operation was interrupted again for the same reason.

The tram operator in Bordeaux did not have specific tools or equipment for removing snow or ice from the power rail, because snow is usually not a concern with Bordeaux's relatively mild climate.

Since this episode, new equipment and practices have emerged to solve the issues related to snowfall and cleaning of the power rail in general:

- A railroad truck specifically designed for cleaning the groove of the running rail and the APS power rail is now available on the market
- Alstom now proposes the installation of heavy duty brushes in front of the collector shoe
- Specific maintenance procedures have been implemented in Rheims (in operation since April 2011), where snow fall is more significant than in Bordeaux. These include:

    - Use of glycol to prevent icing of the APS rail
    - Continuous operation of a tram when snow falls are foreseen to prevent the snow from sticking to the APS rail
    - Ban of applying salt on the streets at a distance of less than 50 cm from the track bed, as salt water leads to current leaks and triggers the tripping of the circuit breaker

Although these measures improve the availability of APS, it is to be noted they are not an absolute mitigation of the risk related to snowfall. Recently, on February 5th 2012, in Bordeaux and February 8th 2012, in Rheims, operation was interrupted for several hours because of snow falls that prevented APS from functioning correctly.

4.5.3 Impact of APS technology on electric distribution scheme

The arrangement of the traction sub-stations is identical for APS and for regular OCS.

4.5.4 Feasibility of fleet retrofitting

APS is currently installed in other cities on Citadis 402 and Citadis 302 trams. The current LUAS fleet is made up of Citadis 401 (Red Line) and Citadis 402 (Green Line).

The retrofit of existing trams to install the on-board APS equipment would require the following modifications:

- Installation of collector shoes
- Installation of roof-mounted batteries
- Installation of antennae under the frame
- Modification of the traction circuit

The Red Line depot has been used in the past to retrofit Citadis 301 trams to become Citadis 401 trams. The necessary equipment is thus available so that the retrofit activity may be carried out in the Red Line depot.

4.5.5 Safety considerations

The electrical safety of the APS system has been demonstrated and reaches Safety Integrity Level 4.[3]

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[3] The allocation of safety integrity levels is specified in standard EN 50126. The safety integrity level varies from 0 to 4, where 4 is the highest level of safety integrity.

The French authority for the safety of guided transportation issues each year a report dealing with tramway safety. Since the opening in Bordeaux of the first tramway line equipped with APS in 2003, the impact of the APS power rail on pedestrian or cyclist safety has never been identified as a concern.

4.5.6 *Energy efficiency*

For safety reasons, regenerative breaking is not possible when running with the APS system, thus energy efficiency is degraded by 15% to 20%.

The cost associated with this increase in the power consumption is difficult to estimate accurately at this stage. In order to carry out this estimate, many assumptions must be made; each of them introduces potential uncertainty in the result.

The main assumptions concern power consumption with regenerative braking and the cost of electricity.

The following table identifies the parameters we took into account for this rough estimate.[4]

cost per MW.h (€)	60
power consumption without regenerative braking (kW.h/tram.km)	13.5
power consumption with regenerative braking (kW.h/tram.km)	11.3
power consumption due to absence of regenerative braking (kW.h/tram.km)	2.3
duration of peak hour (h)	4
headway during peak hours (min)	5
duration of off-peak hour (h)	16
headway during off-peak hours (min)	10
length of the APS section (km)	1.7
number of runs per day	288
distance run per day (km)	478
number of km run per year (tram.km)	174,499
power consumption by year due to absence of regenerative braking (kW.h)	392,623
additionnal cost due to absence of regenerative braking (€)	23,557

The annual additional cost due to the absence of regenerative braking remains relatively low according the calculation above. This is mainly due to the moderate length of the section to be potentially equipped with catenary free system.

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[4] The cost of a MW.h is of course highly variable. The energy consumption per tram.km is the result of a simulation of the running of a 43-metre Citadis 402 tram carried out by Systra on a recent project.

Alstom is currently working on improving energy efficiency by introducing on-board super caps. This solution is more efficient than reinjection of power in the OCS (the classical approach to energy regeneration), because it does not require the presence of another tram on the same section to use this power. On the other hand, the retrofit of existing trams to install on-board super caps appears to involve heavy works which would likely require reinforcement of the tram carshell.

4.5.7 Level of deployment

The APS system is currently deployed in revenue service in the following cities:

- Bordeaux (since 2003)
- Angers (since 2010)
- Rheims (since 2011)

It should be noted that on the French projects, the trams run most of the time on segregated rights-of-way, except at road intersections.

In addition to the projects mentioned above, Alstom has been awarded contracts to implement APS in the following cities:

- Orléans (2006)
- Dubai (2008)
- Brasilia (2009)
- Tours (2010)

4.5.8 Conclusion

The APS solution appears to properly address the constraints specific to the BXD line, by offering:

- Continuous feeding, to cope with unscheduled stops between stations
- A design which takes into account the mechanical stress caused by road traffic
- A high level of safety
- The possibility of retrofitting the existing fleet of Citadis 402

It also meets the requirement for a proven system.

The implementation of the APS system for the BXD line is not prevented by any major technical impossibility and appears feasible to us.

The risk associated with snow fall and ice can be mitigated by proper maintenance and operation procedures, but cannot be completely suppressed as recent experience in Rheims has shown: operation has been interrupted by ice and snow falls several times during the winter of 2011/2012.

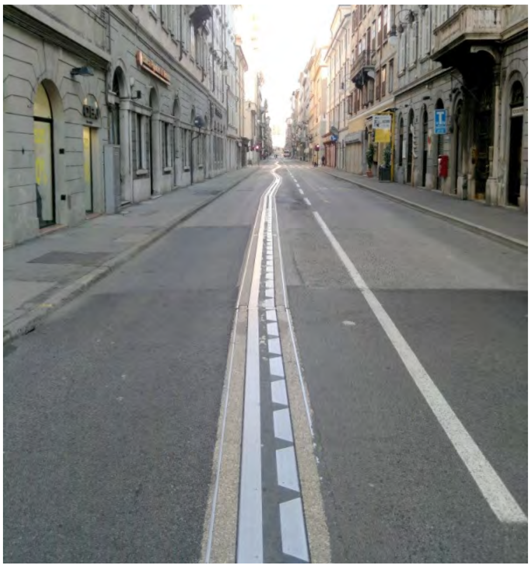
4.6 Suitability of Ansaldo Tramwave system

4.6.1 Fitness for shared running

4.6.1.1 Mechanical aspects

The power rail embedded in the track between the running rails will have to withstand road traffic on the shared running zones.

The Tramwave power rail (originally branded Stream by Ansaldo) has been designed to withstand road traffic and shared running, as it was originally planned to be implemented for buses running in lanes shared with other traffic



View of a Stream power rail on via Mizzoni, Trieste (© L. Fascia)

In Trieste, the embedded power rail has been installed in 2000 to feed electric buses. Although these buses are no longer in service, the power rail has been left in the road bed ever since.

According to Ansaldo, this power rail does not show traces of fatigue or cracks.

4.6.1.2 Running in congested traffic

The Tramwave power rail continuously provides the same amount of power as an overhead catenary, so running in congested traffic is not a concern for a tram fed by Tramwave.

4.6.2 Impact on electric distribution scheme

The arrangement of the traction sub-stations is identical for Tramwave and for regular OCS.

4.6.3 Resistance to weather conditions

4.6.3.1 Flooding

As already explained for the APS power rail, the Tramwave power rail cannot operate when it is covered by water, because such a situation would lead to current leaks when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit.

Flooding of the trackbed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

The Tramwave equipment embedded in the track bed is designed and tested to be watertight.

4.6.3.2 Snow and ice

Snow and ice stuck on the power rail prevent proper contact with the collector shoe and thus may disrupt operation.

The Tramwave system has not yet faced this type of problem because of the mild climate of the location where it has been implemented, but it is likely it would suffer the same kind of operational issue as APS has when exposed to snow and ice.

The solutions adopted for the APS (brush mounted on the tram and specific maintenance vehicle) could likely be adopted for the Tramwave solution.

4.6.4 Feasibility of fleet retrofitting

Tramwave is currently installed on Sirio Tram produced by Ansaldo, and a retrofit of tramways manufactured by another company has never been carried out before.

When contacted about this topic, Ansaldo's representative confirmed the potential interest of the company in such an operation and did not expect any technical impossibility.

He made it clear that in any case the possibility of a retrofit must be confirmed by thorough study of the mechanical and electrical arrangement of the Citadis 402.

The retrofit of existing trams to install the on-board Tramwave equipment would require the following modifications:

- Installation of collector shoe
- Installation of roof super capacitors
- Modification of the on-board traction circuit

The weight of the super capacitor is expected to be lower than the weight of the battery required for the APS solution, so the modification of the Citadis 402 appears technically feasible.

4.6.5 Safety considerations

The Tramwave solution has been recently granted Safety Integrity Level 4 certification by RINA[5] for the 3 km pilot line in Napoli. The previous system (Stream) has been assessed by TUV[6] in 1997.

The risk of pedestrians tripping is mitigated by the flatness of the power rail which is perfectly embedded.

The risk of cyclist sliding on the bare metal surface is similar to the risk of sliding on the top of the running rail, without the risk of having a bicycle wheel trapped in the rail groove.

4.6.6 Energy efficiency

The Tramwave system allows regenerative braking and current injection back to the power rail, in the same way as it is done on sections fitted with OCS.

The overall energy efficiency of the Tramwave system is even in theory slightly higher than the OCS because the copper cables included in the power rail box provide better conductivity than an OCS, although the benefit in terms of energy consumption is minor.

4.6.7 Level of deployment

The Tramwave system has not been deployed as part of a commercial project yet.

The references claimed by Ansaldo so far are the following:

- Implementation of the Stream system in Trieste from 2000 to 2002
- 400 m of test track installed at Ansaldo premises in Napoli
- Pilot line in Napoli on semi segregated running since April 2011

4.6.8 Conclusion

The Tramwave solution appears to properly address some of the constraints specific to the BXD line, by offering:

- Continuous feeding, to cope with unscheduled stops between stations
- A design which takes into account the mechanical stress caused by road traffic

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[5] RINA is an Italian company, member of the IACS (International Association of Classification Societies).

[6] TUV is an Italian testing, inspection and certification entity.

- A high level of safety
- The possibility of retrofitting the existing fleet of Citadis 402

On the other hand, this solution does not properly satisfy two criteria identified by An Board Pleanála:

- There is no guarantee of its performance in circumstances of significant ice and snow fall
- It cannot be considered as fully proven since it has not been implemented as part of a commercial in-service project

The implementation of the Tramwave system for the BXD line is not prevented by any major technical impossibility and appears feasible to us.

The risk associated with snow fall and ice could be mitigated by proper operation and maintenance procedure but cannot be completely suppressed.

In addition, the technical risk associated with a non-proven system cannot be quantified despite the thorough testing performed by Ansaldo so far.

4.7 Conclusion

The paragraphs above analysed the suitability for BXD of the various catenary-free systems available on the market.

The catenary-free solutions which rely on on-board energy storage cannot guarantee the tram will be able to start after many stops and starts in heavy traffic.

For this reason, we consider that the solutions proposed by CAF (Super Capacitor), Siemens (Super Capacitor associated with batteries) and Alstom (Batteries) are not suitable for BXD.

The three remaining solutions under scrutiny have in common their reliance on a continuous supply of power which makes it possible for the tram to stop and start as many times as needed, thus avoiding the risk that trams may find themselves unable to start when stopped in the street due to traffic.

Amongst these three solutions, we have a major concern regarding the mechanical strength of the cover of the embedded loop in the current design proposed by Bombardier for its Primove system.

Moreover, given the constraints associated with electromagnetic flows, it appears doubtful a solution will be easily found to make Primove suitable for shared running and heavy traffic.

For this reason, we consider that, at its current stage of development, Primove is not suitable for BXD.

Alstom’s APS system meets most of the requirements identified for BXD; its design addresses operation in congested traffic, mechanical resistance to heavy traffic, high level of safety.

The retrofit of the Citadis 402 fleet currently run on the Green Line is technically feasible.

The requirement for a proven system is also met, with APS deployed in Bordeaux, Rheims, Angers and Tours.

The vulnerability of the embedded power to heavy snow or ice cannot be denied, but operation procedure and technical features have been developed to mitigate this weakness.

The Tramwave solution proposed by Ansaldo, despite long and thorough testing and the implementation of a pilot line in Naples, cannot yet be considered as a proven system.

On the other hand, the design proposed by Ansaldo meets most of the operational and technical requirement identified for BXD: its design addresses operation in congested traffic, mechanical resistance to heavy traffic, high level of safety.

Based on the available information, the retrofit of the Citadis 402 to implement the on-board Tramwave component appears technically feasible to us.

In conclusion, the market does not yet offer a technical solution that would be perfectly adapted to all of the constraints of the LUAS BXD.

Nonetheless, we consider that two viable solutions, Alstom’s APS and Ansaldo’s Tramwave, meeting the main requirements are available on the market.

Beyond technical feasibility, contractual feasibility must also be determined.

5. INDUSTRIAL CAPACITY

5.1 Situation of Alstom

From a technical point of view, the capacity of Alstom to retrofit Citadis 402 trams is obvious and should not be a concern.

APS has not been developed to be sold as a standalone product, however, but rather to provide Alstom a competitive advantage when selling trams. We do not have information that would indicate whether Alstom would be interested in carrying out a retrofit.

The French authority in charge of ensuring fair competition among bidders in public tenders has obliged Alstom to publish a thorough description of the interface between the track-side APS equipment and the on-board APS equipment, in order to make it possible for other manufacturers to propose trams which are compatible with the APS infrastructure.

Following this publication, CAF was able to propose APS-compatible trams as part of its bid for Bordeaux’s fleet extension in 2011.

5.2 Situation of Ansaldo

Although we suspect that it would be technically possible to retrofit Citadis 402 trams with on-board Tramwave equipment, this assumption would need to be confirmed by Ansaldo.

Once again, we do not have information regarding the interest that Ansaldo may or may not ultimately have for carrying out such a retrofit operation.

Tramwave is also a proprietary solution, covered by patents, and despite the simplicity of the on-board equipment, another tram manufacturer would not be allowed to provide Tramwave-compatible vehicles, except if this has been agreed upon beforehand with Ansaldo at the time the BXD section is installed.

5.3 Conclusion

The retrofit of Citadis 402 trams for use with a catenary-free system appears feasible to us from a technical perspective. We do not know, however, whether the manufacturers would be interested in carrying out such a retrofit.

The only approach to mitigate the long-term risk of monopoly for the procurement of new trams is to reach a contractual arrangement to this effect with the initial manufacturer.

Such an agreement would oblige the manufacturer to supply any future tram suppliers with the components which ensure compatibility with the catenary-free infrastructure or to provide a detailed description of the interface between the trackside and the on-board equipment so that other manufacturers may design trams that are compatible with the proprietary infrastructure.

6. EXTENT OF THE RETROFIT

6.1 Operational requirement and context

The LUAS BXD project includes an interconnection with the existing Red Line, whereas currently no connection exists between the Green and Red Lines. This interconnection is planned to be implemented when the Green Line extension crosses the Red Line in O'Connell Street and in Marlborough Street.

The existing tram fleet of the Green Line will be used on the extended Green Line.

In addition, RPA wants the Red Line fleet to be able to run on the Green Line and vice versa.

6.2 Technical consequences

The interconnection of the two lines has deep consequences because transitions between a section fitted with OCS and an OCS-free section is usually made at station.

In other words, it means that the connection between the Red Line and the Green Line on O'Connell Street near the GPO would require retrofitting the Red Line up to the next station before the connection, to install OCS free power infrastructure in addition to the existing OCS.

The existing Green Line fleet (Citadis 402) must be retrofitted to be able to run on the extension fitted with OCS-free power supply.

The current requirement for Red Line trams (Citadis 401) to be able to run on the Green Line would necessitate the retrofit of the entre Red Line fleet, as well

6.3 Conclusion

The retrofitting of the existing Green Line fleet is a necessity and cannot be avoided. Despite its cost, the retrofit of the Citadis 402 appears feasible.

The requirement for interoperability between the Red and the Green Line fleets has a major impact on rolling stock (retrofit of 40 Citadis 401) and installation of a few hundred meters of OCS-free power supply infrastructure on the Red Line.

The technical feasibility of the retrofit of the Citadis 401 is not guaranteed at this stage, and would likely require deeper works than the retrofit of Citadis 402.

The benefit of the interoperability of the Red and Green Line is not obvious to us. During our visit, we learnt that both depots have equivalent capabilities, so there is reduced need to transfer trams from one line to the other on a regular basis.

Given the huge expected costs and reduced benefits, we do not consider it is worth implementing the full interoperability of the two lines.

A cheaper alternative to consider is to maintain the interconnection of the tracks between the two lines, without implementing the continuity of the power supply. In the event the operator wishes to transfer a Red Line tram to the Green Line depot, this tram could be towed when running over the OCS free section.

7. INVESTMENT AND OPERATING COSTS

Following the technical analyses carried out above, the cost aspects will be addressed for the two solutions which have been considered as potentially suitable for BXD line: Alstom's APS and Ansaldo Tramwave.

The information is available to SYSTRA based on past and recent involvement in bids and cooperation with operation companies.

Whilst such information cannot be site specific and has to a certain extent been generalised due to commercial sensitivities they are however based on SYSTRA's recent practical and considerable knowledge and experience in the field.

Regarding the operation scheme, *Luas Broombridge St. Stephen's Green to Broombridge (Line BXD) Environmental Impact Statement (Book 1)* states on page 109 §7.4 that the duration of the trip is expected to be 24 minutes, and the foreseen headway is 3 minutes.

From these operation parameters, we deduct the minimal theoretical tram fleet should be 16 trams (8 trams running in each direction at each given time). Since some additional trams are usually needed to provide operational flexibility, we assume 18 new trams will be purchased.

7.1 Investment costs

The investment costs provided below are based on recent contracts or bids. These costs have to be considered cautiously, keeping in mind the high variability of the prices proposed by the tramway providers from one project to another.

We have observed that, depending on the level of competition and the desire of a provider to get a first reference for a new solution, the price may vary by +/- 25%.

7.1.1 Alstom APS

The APS system is made of on-board equipment and track side equipment.

To this date, on-board equipment has always been delivered on new trams.

The cost of this on-board equipment *delivered on a new tram* is estimated to be around 300,000 €, in addition to the basic cost of the tram.

A retrofit of in-service trams to install on-board APS equipment has never been performed, so we lack references.

Nonetheless, given the specificity of the operation, we can estimate the retrofit of a Citadis 402 will add an extra 100,000 € approximately to the price of the on-board APS equipment.

In the case of a Citadis 401, more extensive modifications may be needed; we cannot estimate the cost of such an operation.

The cost of the APS track side equipment is estimated to be 1,850,000 €/km.

The overall additional cost for APS implementation is estimated to be about 19,000,000 €.

For price breakdown, refer below to 7.2.3

7.1.2 Ansaldo Tramwave

Ansaldo's Tramwave system in not yet installed anywhere. On the other hand, Ansaldo has participated in some tenders but no price was officially communicated.

Despite this lack of information, we estimate that capital costs of the Tramwave on-board and track-side equipment should be of the same order of magnitude as the costs related to Alstom's APS system.

Given the specificity of a retrofit operation carried out by Ansaldo on the Citadis 402 trams, involving significant redesign activities, we expect that the cost of retrofit will be higher than that of the equivalent retrofit made by Alstom with its APS system.

Nevertheless, we do not know the amount Ansaldo could ask for this retrofit. In particular, manufacturers may be willing to offer a competitive price if the contract is considered to be important.

7.2 Operation and maintenance costs

7.2.1 Alstom APS

The trackside APS equipment requires some maintenance effort, especially the power boxes embedded in the track bed.

The maintenance effort for the fixed APS equipment is estimated to cost 75,000 €/year/km.

In addition, the current design of APS is not compatible with regenerative braking, so the power consumption will be increased by 15% to 20% on the section equipped with APS.

As the calculation carried out in §4.5.6 showed, the annual cost associated with the relative reduction in energy efficiency is roughly 25,000 €.

7.2.2 Ansaldo Tramwave

The Ansaldo Tramwave is not yet in revenue service, so there is no information available regarding the operation and maintenance cost.

Ansaldo Tramwave allows regenerative breaking, so energy consumption will not be increased as compared to OCS.

7.2.3 Cost Summary

The following table summarizes the additional investment and operating and maintenance (O&M) cost associated with the implementation of APS (as compared to an OCS-only system).

This table is based on the estimated unit costs provided above and the hypothesis that only BXD line will be equipped with APS (not retrofit of the red line fleet).

According to these hypotheses:

- 1.66 km of tracks shall be equipped with APS
- 26 trams shall be retrofitted
- 18 new trams shall be purchased (estimate based on 24 minutes trip and 3 minutes headway)

Investment cost	€
APS infrastructure	3,071,000
Cost of fitting APS equipment on new Trams	5,400,000
Cost of retrofit	10,400,000
Total	18,871,000
Yearly O&M costs	€
Additional power supply cost	25,000
APS maintenance cost	124,500
Total	149,500

APPENDIX 1 - TERMS OF REFERENCE FOR REPORT ON ALTERNATIVE POWER SUPPLY SYSTEMS

Objective

Examine the feasibility, primarily from a technical and economic perspective, of employing an alternative to the Overhead Cable System (OCS) proposed in the draft Railway Order, in the visually sensitive areas of Dublin city centre.

Considerations

The sensitive area for the purpose of the study is from St. Stephen's Green to the north end of O'Connell Street, including Dawson Street, College Green, O'Connell Bridge and the GPO. The south-bound leg of the one-way system (Parnell Street to College Street) is not considered sensitive.

The author should become familiar with the existing LUAS systems as already serve Dublin Region, and how the BXD line will integrate with same, and also longer term transport plans for the region.

The study should focus only on systems that are developed and commercially available. Systems employed in cities such as Bordeaux, but also more recently in Nice, Reims, Orleans and Angers should be included for consideration (and any other relevant locations).

Up to date information on such systems should be gathered, including consultation with system providers and operators, where possible. Up to date cost estimates should be used.

The report should identify the most relevant technology/ technologies applicable to the LUAS BXD requirements, and consider the potential for use on LUAS BXD, including:

- System Reliability
- Suitability for the proposed level of shared running (with cars buses etc.) and implications for reliability/ traffic management
- Ability to cope with adverse weather conditions, e.g. snow/ice or heavy rainfall (and possible implications for the roads authority or the environment if new response procedures are required)
- Safety implications for cyclists in a shared running environment
- Energy considerations
- Necessity and extent of retrofitting on existing fleets of trams
- Likely cost differential (both capital and operational) that an alternative to OCS would mean for the overall project.

APPENDIX 2 - REFERENCE DOCUMENTS

Title of the document
Greater Dublin Area - Draft Transport Strategy 2011-2030 - 2030 vision
Inspector report for case 29N.NA0004 by B. Wyse
Luas Broombridge Oral Hearing - Proof of evidence - Overhead Conductor System (OCS) by Paolo Carbone
Luas Broombridge Oral Hearing - Proof of evidence - Construction and Operational Traffic Management by Eoin Gillard
Dublin Chamber of Commerce - Submission to An Bord Pleanala - RPA Railway Order for Luas Broombridge (dated 13th August 2010)
Letter: Construction operation and maintenance of a light railway system from St Stephen's Green to Broombridge, Dublin, by Alan McArdle (dated 3rd February, 2012)
Luas Broombridge Oral Hearing - Dublin City Council - Opening Address by Gerard Meehan B.L. (dated 20 May 2011)
Luas Broombridge (Line BXD): presentation for Enginers Ireland (dated 21 February 2012)
Development of Luas & the Next Phase of implementation - Luas Broombridge: presentation by Michael Sheedy and Jim Kilfeather (dated 21 February 2012)
Line BXD Power Description by RPA, rev 01 (dated 6 march 2012)
Kylemore Ess Equipment Layout reference by Ansaldo CZ-AXX-600-EM-0078, revision Z04 dated 30/06/04
Line BXD -Structures- Substation- Broadstone reference BXD-SS-29-E-0, no revision, no date
O'Connell BXD, Broadstone Single Line Diagram, reference A-BXD-0000-PS-0002, revision A01, dated 10/05/2011
Overhead Contact System Traction Power System Distribution Single Line Diagram reference A-BXD-000-PS-003, revision A01, dated 13/05/2011
St Stephens Green Ess Equipment Layout by Ansaldo, reference CZ-XBX-600EM-0122 revision Z03, dated 20/05/04
St Stephens Green Substation Single Line Diagram, reference A-BXD-0000-PS-0001 Revision A01 dated 10/05/11
Broombridge Line and Depot Single Line Diagram, reference A-BXD-0000-PS-0004 revision A01, dated 07/05/11
Substation Relocation Works Equipment & Cable Routing Layout, reference T-MN-7178B-PS-01001 revision T01 dated February 2010
Railway Works, Line BXD - Alignment Details - Cathal Brugha St. Dominick LWR reference BXD-R0-29-C-D, dated June 2010
Railway Works, Line BXD - Alignment Details - Eden Quay to Cathal Brugha St. reference BXD-R0-29-B-C, dated June 2010
Railway Works, Line BXD - Alignment Details - Grafton Street to Eden Quay reference

Title of the document
BXD-R0-29-A-B dated June 2010
Railway Works, Line BXD - Alignment Details - St Stephen's Green West to Grafton Street, reference BXD-R0-29-0-A dated June 2010
Draft Typical Cross Section - Double Track Embedded Shared by RPA (not dated, no author)
Draft Typical Cross Section - Double Track segregated Option 1 by RPA (not dated, no author)
Luas Broombridge (Line BXD): Environmental Impact Statement (book 1 of 5)
Luas Broombridge (Line BXD): Environmental Impact Statement (book 2 of 5) Area 29 St Stephen's Green to former Broadstone railway cutting
Luas Broombridge (Line BXD): Environmental Impact Statement (book 4 of 5): Maps
An Board Pleanala: Functions of the Board (extract of a web site)
Planning & Policy: Zoning Objectives dated April 2010
Overall map of Dublin showing the Heavy Commuter Line, the Existing Tram Line and the proposed BXD (drawn by hand, no reference)
Defining Dublin's Historic Core: Realising the Potential of the City Centre and its Georgian Squares for Citizens, Business and Visitors by Geraldine Walsh, Stephen Coyne and Graham Hickey (2010)
Tram System in Bordeaux: Report on the tram System and underground Power Supply for Dublin City Business Association by Brendan Finn, dated 7th December 2007
A spatial Vision for Dublin (April 2009) by Hendrik W van der Kamp

Overhead wires free light rail systems

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Corresponding author: Margarita Novales.

Authors:
Margarita Novales. Civil Engineer, PhD. Railways Associate Professor. La Coruña University.
Address: ETS Ingenieros de Caminos, Canales y Puertos. Campus de Elviña, s/n. E-15071. A Coruña. Spain
Telephone: +(34)981167000 Ext.:1452
Fax: +(34)981167170
E-mail: mnovales@udc.es

ABSTRACT

Light rail systems are experiencing a revival in several countries in the world. Nevertheless, they are facing a more and more demanding market which implies continuous new evolutions and technologies. An example of this fact is related to the requirement of avoiding visual intrusion in some areas of cities which are more sensitive to visual impact.

This fact has led to the implementation of new solutions that try to avoid the need for overhead contact wires through the whole network or through the lengths between stations. These solutions are based, generally, in the use of new embedded third-rail systems; the use of on-board energy storage devices; or the use of electric energy produced on-board the vehicle.

This paper is focused in the explanation of these technologies, their applicability, as well as their advantages, risks and inconveniences, in an attempt to clarify available options and their reliability.

1 INTRODUCTION

Although streetcars disappeared in many cities around the middle of the last century, nowadays a revival of this technology is taking place, in most cases improving the performance of the system by the use of type B right of way category [1], that is, giving to transit a longitudinally physically separated right of way, which will improve operational speed, frequencies, availability and punctuality of the system. Several countries can be cited as examples of this revival, such as Spain, France and the United States.

Nevertheless, nowadays light rail systems are facing a new requirement related to environmental impact, specifically to the visual intrusion produced by overhead contact system (OCS). OCS typically consists of vertical support poles located either on the center of the track, or on one or both of its sides, from which the isolators and the wires which provide electric power to the vehicles are suspended. Electrical energy is transferred from the overhead wire to the vehicle by a roof-mounted pantograph [2].

It is true that in most cases OCS should not be an important environmental problem, because the solutions usually provided for urban systems (speeds up to 70 km/h), consists only of one contact wire suspended directly from the poles, or by means of a short auxiliary wire. If this disposition is compared with the initial state of many streets (see Figure 1), it is clear that the effect of OCS will be at most similar to the one of the electrical cables existing in many cases.

On the other hand, there are several measures to minimize the negative visual effect of OCS, which are very well explained in [3].

Nevertheless, there will be some situations in which special care must be taken in relation to visual intrusion. This is the case of areas with high significance, as historic city centers, emblematic places of a metropolitan area, parkways, etc. In addition, there are some other locations in which the existence of OCS may cause problems, as when a light rail route travels under bridges without vertical clearance to allow OCS installation, or in places where it is difficult to install wires, as in tunnels or at large intersections. There are even some cities in whose centre the use of aerial wires is forbidden (as is the case of some areas of Washington DC).

Finally, OCS normally uses the track rails as a return circuit for electric power to the substations. This fact may lead to stray currents, a phenomenon by which the return current follows the least resistant path to earth instead of the rails. In the case of soil and ferrous objects stray currents cause an electrolytic effect which can rapidly corrode any electrically conducting objects and in severe cases can lead to structural failure. To prevent this from happening, important isolation measures must be taken, which can raise construction costs of light rail systems.

Through the history of trams several cases of OCS-free systems have been implemented, as it is the case, for example, of New York and Washington DC. These solutions were the result of a possibly overzealous desire by these cities to eliminate all exposed wiring in the downtown districts. It resulted in an installation that was not only much more problem-prone than OCS, but it also was more costly to construct, maintain, and operate [4].

Nowadays, mentioned reasons have led several streetcar manufacturers to search for new solutions to provide electric power for the streetcar vehicles. In many cases these solutions are quite similar to the ancient ones, although they are improved in several aspects. They can either be combined with OCS on different stretches of the network, or substitute OCS in the whole track.

These new solutions will be presented in this paper.

2 EXISTING SOLUTIONS FOR OCS-FREE LIGHT RAIL SYSTEMS

There are, mainly, three alternatives to prevent the use of contact wires in light rail systems with right of way categories C (shared) and B (reserved) [1], which are the following:

- The use of an embedded third rail (ETR), located between the running rails at the same level as the rest of the street. The traction power supply can be either by contact or inductive. In any case, as the right of way can be utilized, at least in some areas, by other street users (pedestrians, cyclist, private cars), safety must be guaranteed. This is achieved by allowing that only the areas of the ETR which are under the vehicle be energized.
- Energy storage on-board the vehicle, by means of batteries, super-capacitors, flywheels, etc. These elements will have to be charged either during the vehicle circulation, or when it is stopped at stations.
- Electric energy produced on-board the vehicle, by means of diesel-electric generators, fuel-cells, etc.

These technologies will be explained in the next sections.

2.1 Embedded third rail (ETR) technology

This technology is the only one that means a real alternative to OCS if elimination of wires along the whole network is desired. Nevertheless, existing implementations do usually not affect the whole networks, but are combined with OCS, using the ETR solution only in sensitive areas.

General advantages of this solution are:

- Preservation of the urban visual environment.
- Total safety for pedestrians and road users.
- Avoidance of access problems for emergency vehicles (as firefighters) to building facades.
- Prevention of conflicts with arboreal vegetation of the streets.

On the other hand, there are still some inconveniences in this solution, which are supposed to be counteracted with time and experience, as the concerns about its operation with rain, ice and salt; the construction and maintenance costs; and the reliability of the system.

Nowadays, there are three different ETR technologies, designed by three different companies, with their corresponding patents and with different levels of development.

2.1.1 Alstom' APS system

In this solution, the 750 V-dc ETR is made up of 8 m long conducting segments separated by 3 m insulating joints. Power is supplied to the conducting segments by underground boxes every 22 m.

The delivery of power to the conducting segments is triggered by coded radio dialogue between the vehicle and the ground, and only occurs once the conducting segment has been covered by the tram, ensuring total safety. The electricity transmitted through the ETR is picked up by two collector shoes located in the mid-section of the tram, while a block of roof-mounted batteries allows the vehicle to maintain power at stations or if a power control unit fails [5]. The whole system is shown in Figure 2.

Bordeaux (France) is the first city in the world to have opted for this completely new technology on 14 km of its 44 km long tram network. It has been operating since the end of 2003 [5].

This solution had some initial troubles, due to drainage problems in buried power boxes. These troubles were solved and APS is now operating successfully in Bordeaux at 99.8% reliability since the end of 2005. Three other French cities, Angers, Reims and Orléans, decided in 2006 to install APS on their new light rail networks, and Alstom won its first contract for a system outside Europe last year (Dubai's Al Safooh Tramway) [5].

The main advantages of this solution, apart from the general ones of ETR solutions, are:

- It is a mature technology that has been proved in actual applications (initial problems properly solved).
- Performance levels equal to those of a conventional tram in terms of comfort and speed.

The greater inconvenience of this technology, as of all ETR solutions, is related to the infrastructure's cost. Indeed, in the existing implementation the cost of each meter of APS system is around 7 times the cost of the equivalent OCS. Nevertheless, it is important to note that OCS usually represents only around 3% of the whole cost of a tramway project. If APS is applied in the most sensitive zones (for example, 30% of the network, as is the case of Bordeaux), it will lead to an increase of project' cost around 7·3·0.30=6.3%, which seems to be an affordable amount in a project of these characteristics. For French applications, Bordeaux is the one with a greater percentage of APS in relation to the length of the network. Only the Dubai project is going to have the complete network provided with APS.

APS leads to an increase of vehicle weight of around 1000 kg, which is not very significant. But the ability to regenerate energy into the power distribution system is no longer possible. Therefore the vehicle has to either store the energy locally or dissipate it into a brake resistor which must also be carried in the vehicle [6]. In relation to maintenance costs, Alstom assures that maintenance overcost due to APS is marginal (less than 3%).

Finally, concern exists in relation to the potential for stray currents where the roadway is wet or wet with a salt solution for snow clearing [2]. On the other hand, it is probable that extra care must be taken in the case of extreme-weather cities, for avoiding the contact strip to suffer from ice and salt build-up across the conductors.

2.1.2 Ansaldo's TRAMWAVE system

The TramWave technology is quite similar to APS. Again, the power supply system consists of a 750 V-dc third rail embedded in the permanent way, provided by a contact line that only energizes a small section as the vehicle passes over it.

TramWave is the result of the technical evolution and adaptation to tram vehicles of STREAM (Electric Power System with Magnetic Attraction) system, developed by Ansaldo more than ten years ago, and successfully tested in Trieste's tyre vehicles (Italy), specifically in hybrid buses.

In this case, the basic building block of the TramWave system is a modular unit, 3 or 5 m long, 30 cm wide and 12 cm high, that contains all the elements needed for the correct functioning of the ground-level power supply system.

A series of steel contact plates are located at intervals on the top of the box (see Figure 3). The modular boxes are joined together to form the power supply of the light rail line. The modules are placed in a "continuous conduit" that contains the positive feeder and a negative cable to protect the line.

The power collection is made by means of a retractable pickup shoe placed in the centre of vehicle's truck. It is equipped with hybrid magnets which attract the power element located at the bottom of the module. The power element is flexible, in such a way that it can be elevated and when it is in contact with the top part of the module the ETR segments in contact with the shoe are energized (see Figure 3).

The system is designed in such a way that the energized length is not greater than 1.5 m (three segments at the most), remaining always under the vehicle.

Ansaldo assures that this system has lower maintenance requirements than the OCS, because any breakdown will affect only one module, which is automatically identified by the diagnosis system, and can be replaced by another complete module in barely 30 minutes. In addition, the failure of one module does not prevent the vehicles from running over the track, and the replacement can be made when the line is in service.

TramWave can be commuted from overhead to ground supply, even when the vehicle is moving, either automatically or by the driver's order. In addition, it can be combined with on-board energy storage systems, and the power supply can be used to recharge them. In the same way, the vehicle can be disconnected from the supply line, even when it is moving, and run autonomously with energy stored on-board.

An additional advantage of this system is the fact that the return current is transferred via the contact plates and the tracks do not need to be used for this purpose. This is an important feature since in this way the TramWave eliminates the effects of stray currents, avoiding the need for track electrical isolation.

Finally, this power supply system can also be used by electrical vehicles which have rubber tyres. Consequently, the tramway line equipped with the TramWave system can become the backbone power line for different vehicle fleets and/or a global network that uses it as a mobile charging station for battery-powered vehicles.

The main drawback of this system is that it has not been applied to any real system, although tests for the feeding modules on the Naples (Italy) test track were successfully completed and there is now an actual trial version of the system equipping 600 m of the Naples-Poggioreale experimental line. Therefore, there are not enough data to make conclusions about cost and reliability of the system.

Finally, as for the case of Alstom's APS solution, there is concern as to the potential for stray currents where the roadway is wet or wet with a salt solution for snow clearing [2].

2.1.3 Bombardier's PRIMOVE system

The PRIMOVE system is similar to APS and TramWave in some aspects, as that the wires laid beneath the ground are connected to the power supply network, and are only energized when fully covered by the vehicle.

Nevertheless, the technology for getting the energy from the ETR is very different, as it is based on the inductive power transfer of a transformer (see Figure 4), without contact. While a magnetic field is generated, energy is stored in the primary electric circuit, that is located between the rails of the track, and the secondary circuit, under the vehicle, transforms this energy field in electric power for tram's operation.

In this case, to get the energy, a pick-up coil underneath the vehicle turns the magnetic field created by the wires in the ground into an electric current that feeds the vehicle's traction system.

This system is able to provide the energy needed for running up to 40 km/h over a 6% ramp.

Additionally, vehicles with PRIMOVE can be provided with the MITRAC energy saver technology by Bombardier (see section 2.2.2).

PRIMOVE is undergoing extensive testing at the test track of the Bombardier site in Bautzen, Germany, simulating regular operation. Additionally, Bombardier announced on May 2010 that PRIMOVE is going to be tested in German Augsburg's line 3 in a test branch 800 m long.

An important advantage of this system in relation to the two previously presented is that there is no direct contact during energy transfer, and therefore, there is no wear of parts and components. This is supposed to keep service and maintenance costs at a minimum.

On the other hand, Bombardier assures that this system is resistant to all weather and ground conditions including storms, snow, ice, sand, rain and water, as well as that it gets the same vehicle performance as with conventional OCS.

The main drawback is, as for the TramWave system, that it has not been tested yet in any real application, although the results of the Augsburg test will be of interest to know more about its performance. Bombardier assures that the initial construction costs lie far below those of any comparable solution on the market, but it can not be contrasted until the Augsburg results are available.

Additionally, depending on the frequency of operation, the magnetic or inductive coupling may also produce some local electromagnetic effects. On the other hand, this system has the same problem as the Alstom's one in which is related to energy regeneration [6].

2.2 Energy storage on-board the vehicle

The main disadvantage of ground power supply is, probably, that like in the case of OCS, it involves the installation of fixed infrastructure, with the corresponding construction and maintenance costs, and the additional problems to provide it to an existing network.

An alternative to these solutions is the use of on-board energy storage systems. These technologies emerged, in the first stage, not in order to avoid the existence of overhead wires, but to improve the energy efficiency of light rail systems.

Indeed, one way to reduce the energy consumption of trams is by using of regenerative braking, which is widely extended in the railroad field, so as to make the most of the kinetics energy that has to be dissipated during the braking process (that is very frequent in cities). But in the initial stages, for regenerative braking to be effective, there had to be other vehicles around to absorb the surplus power being fed back into the OCS, especially when traction is of dc type. Too often, power produced by traction motors in braking mode ended up lost heating resistor banks.

To prevent this from happening, trams started to be provided with on-board energy storage systems, in such a way that braking energy is saved for use when necessary due to points in the vehicle's demand, as is the case of acceleration. But very soon, the technicians were conscious of the additional possibilities of this kind of technology to avoid the use of overhead wires in specific branches of the network.

The most common technologies of on-board energy storage systems are batteries and, most recently, super-capacitors. Other systems, as flywheels, have been used in some vehicles but they do not seem to be a solid option. It can be due to the risk implied by having high speed rotating machinery in close proximity with passengers, as well as to the flywheel's concentrated weight and inertia. In any case, perhaps further study of flywheels might be warranted because of their excellent charge/discharge cycle life, even though they have not so far seen recent service acceptance comparable to batteries or super-capacitors.

It must be highlighted that the vehicle which has an on-board energy storage system is able to run even when it experiences poor contact on the wires, due, for example, to ice formation, maintaining speed until electrical contact can be regained. On the other hand, the zones without overhead wires are obtained without need for extra installations or special investments.

A comparison between different on-board energy storage devices is made in Table 1.

2.2.1 Batteries

Battery storage is a proven and mature technology. It provides a relatively good weight-to-power ratio and low cost. One of its major disadvantages is that the battery is affected by temperature, which at low temperatures results in loss of capacity, and at high temperatures can cause plate buckling leading to short circuits and loss of voltage, or even electrical fires in extreme cases. Batteries are susceptible to rapid charge cycles and deep discharges, which can result in some loss of life expectancy and overall performance. A further disadvantage is that most batteries require routine maintenance and inspection and also regular charge and discharge cycles to maintain peak performance [6].

Nevertheless, the rapid development of Nickel-metal hydride batteries (NiMH) in recent years has allowed several tram manufacturers to offer an alternative to both overhead and ground power supply.

In November 2007, Nice became the first city in France to use battery-powered Alstom Citadis vehicles. Each vehicle is equipped with roof-mounted NiMH batteries which are charged from the OCS and allow the vehicles to run through two historic squares where OCS has not been installed. The batteries allow the vehicle to operate at up to 30 km/h, albeit with a lower rate of acceleration than OCS [5].

Alstom, CAF, and other manufacturers are also investigating the potential of lithium-ion (Li-Ion) batteries, which offer higher density energy storage than the NiMH cells, and which are having an important development due to automotive industry.

As another example of battery use, Kawasaki has been testing its Swimo OCS-free vehicles in the Japanese city of Sapporo [7]. Swimo uses Kawasaki Gigacell NiMH batteries, which can be fully charged in five minutes through the 600V-dc OCS. This allows Swimo to operate for up to 10 km on non-electrified lines under standard Japanese operating conditions, although Kawasaki has run the vehicle for 37.5 km during tests without recharging the battery. Swimo can also store energy from regenerative braking and use it for traction [5].

Nevertheless, although NiMH batteries have the necessary energy storage density in terms of kWh/kg, it seems to be generally accepted that their life in terms of charge/discharge cycles in no way matches the light rail vehicle's requirement for 2 million cycles over 10 years [8]. On the other hand, Li-Ion batteries technology seems to be in a very initial stage of research for their use in transit applications. This is the reason that is leading to the imposition of super-capacitors instead of batteries. In any case, it will be worthy to follow future developments in this field, given by automotive industry, and check their applicability to transit systems.

2.2.2 Super-capacitors

Super-capacitors are an improved and more challenging version of capacitors for transit applications. In a conventional capacitor, energy is stored by removing electrons from a metal plate and depositing them on another. This charge separation between the two plates can then be harnessed in an external circuit. The amount of charge stored is a function of the size and material properties of the plates, while the flow of energy between the plates is dictated by the composition of the dielectric. By sandwiching different materials between the plates, different voltages can be stored [5]. In any case, the capacity of conventional capacitors is really low, and is not suitable to match the requirements of transit vehicles.

Super-capacitors do not have a conventional dielectric. Rather than two plates separated by an intervening substance, these capacitors use plates that are in fact two layers of the same substrate, and their electrical properties, the so-called electrical double layer, result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of plates with a much larger surface area into a given size, resulting in extraordinarily high capacitances in practical-sized packages.

The storage capacity of double-layer capacitors can be improved by using a nanoporous material such as activated carbon. A single gram of activated carbon has the same surface area as half a soccer pitch [9].

The advantage of the super-capacitor is that it has a high charge/discharge rate and can absorb the immediate energy produced by braking energy regeneration. Its low equivalent series resistance means that power loss in the device is small and the units can run at typically 95% efficiency. Furthermore, super-capacitors can be completely discharged without reducing their service life, and extreme temperatures have very little impact on their performance [6, 9].

In the last years, several trams provided with super-capacitors have been developed by manufacturers. These solutions imply an increase in vehicle weight and cost, but it is compensated by energy savings in general cases.

Alstom's STEEM solution

Alstom has developed its STEEM (Maximal Energy Efficiency Tramway System), which is being tested on line T3 in Paris (France). An Alstom Citadis vehicle has been fitted with a 1.4 tonne roof-mounted unit housing 48 super-capacitor modules. These modules can be completely charged in 20 seconds through the overhead system or a charging station, and can also take charge from the regenerative braking system [9].

The test vehicle is capable of travelling 300 m with 300 passengers on board at up to 23 km/h, with 30% of the power remaining when it reaches the next stop. However, Alstom says that it is possible to mount a second Steem unit on the roof of a Citadis to increase the range of OCS-free operation. The super-capacitors can still take energy from the regenerative braking system, even when the vehicle is drawing traction power from the Steem module [9].

Bombardier's MITRAC solution

Bombardier has developed the MITRAC system, based on the super-capacitors technology, and made a demonstration trial in the Manheim network (Germany), which has been in normal service since 2003 [8].

This vehicle has two powered trucks, each with two motors. One of them has been equipped with a MITRAC unit, while the other is supplied conventionally so that the energy performance of the two halves of the tram can be compared. Energy savings of around 30% were demonstrated by the MITRAC half of the vehicle for most of the year, compared to its conventional twin [8].

MITRAC weighs about 450 kg, and the external dimensions are 1900 mm long, 950 mm wide and 455 mm deep [8].

The vehicle provided with the MITRAC unit was consistently able to travel through a simulated 500 m gap reaching speeds up to 26 km/h with the pantograph lowered, despite the fact that it has only one MITRAC unit fitted rather than a normal pair [8].

CAF's ACR solution

CAF (Construcción y Auxiliar de Ferrocarriles) has been developing its ACR (Rapid Charge Accumulator) OCS-free system in conjunction with Trainelec and Aragon Technical Institute [5].

The super-capacitors can be fully charged, while the train is stopped in a station, in around 20 seconds [5]. In addition, as for the rest of technologies, the system recovers the energy stored on the journey and the braking energy too [10].

The roof-mounted accumulator is suitable for rolling stock of any manufacturer, as well as any new or existing installations or infrastructure [10]. It can be complemented with NiMH batteries as back-up for solving super-capacitor's failure situations.

The implementation of ACR in a light rail vehicle increases its weight around 2 t per module. With the common solution for OCR-free systems of two modules, this leads to an increase of 4 t. The increase of weight is compensated with the energy saving.

The system has been tested during one year, in a first stage in Vélez-Málaga, and in May 2010, the first tram provided with ACR initiated its commercial service in Seville (Spain). These vehicles will allow the OCS to be definitely eliminated in the whole Seville network but at stations [11].

CAF assures that these vehicles can achieve a maximum autonomy of 1000 m, but in the commercial service 500 m are guaranteed with active auxiliary systems [11].

In relation to vehicle's overcost due to super-capacitor provision, CAF assures that in the next developments it can be around 10-15%. Super-capacitor's life depends on temperatures and charge/uncharge cycles. For Seville, this life is expected to be around 7-8 years.

An illustration of ACR's performance is presented in Figure 5.

Siemen's Sitras HES solution

The Siemen's Sitras-HES solution consists of two energy storage devices: the Sitras-MES (super-capacitor mobile energy storage unit) and a NiMH battery. This concept combines, as CAF's ACR, the benefits of the super-capacitors with the characteristics of a traction battery. The capacitors recharge faster and deliver the energy faster than traction batteries, which release their stored energy over longer periods.

The roof-mounted modules have been installed in spare roof space on a Siemens Combino Plus vehicle, and are electrically connected to the vehicle's energy supply point. This means that Sitras can be easily retrofitted to older vehicles, including those of other manufacturers [5].

Sitras-HES can complete its charging cycle in 20 seconds, taking power from the catenary or a charging point while the vehicle is standing in a station. This provides sufficient power for the vehicle to run independently for up to 2.5 km, depending on the operating conditions [5].

Siemens began work on this system in September 2007, and it has been used on Lisbon's Metro South light rail network (Portugal) since November 2008. Indeed, the Sitras-HES is being successfully used in everyday passenger transport operation. The test vehicle is operated without overhead power supply on a 2.6% gradient with auxiliary power of 5 kW and a maximum speed of 30 km/h [5].

In Germany Sitras has also been approved for use in public passenger transportation, in accordance with BOStrab (a legal ordinance governing the manufacture and operation of streetcars) [5].

2.3 Electric energy produced on-board the vehicle

There are different possibilities to generate electric energy on-board the trams. They are, basically, fuel systems such as hydrogen fuel-cells, hydrogen internal combustion engines, and diesel-electric generator sets.

The hydrogen-based systems have not been yet advanced to a point where they can be applied to a transit vehicle for commercial application. Fuel-cell technology continues to be developed along with the infrastructure required for hydrogen fuel-cells (storage tanks and pumping equipment for refueling the vehicles), and while it seems to be a promising technology, it is not still mature enough. Finally, diesel-electric generator sets have been used in various applications in the world, but the industry is moving away from fossil fuel based systems [2].

Therefore, this third range of solutions does not seem to be a good option for avoiding the use of OCS wires in a short-term future.

3 CONCLUSIONS

The only solution that can absolutely avoid the use of OCS wires in the whole network is the ETR. Among the different available technologies, some of them have a high degree of development and testing, and others are more in the testing stage. In general, they are capital cost intensive, it is supposed that they will have higher operation and maintenance costs and they will require more substantial safety certification [2]. In some of them, it is necessary to assure the prevention of stray current problems under some environmental conditions.

On the other hand, an additional concern can be related to the proprietary nature of the technology and the potential to become dependent on a single supplier.

In general, it must be highlighted that the implementation of the ETR technology in all or part of the network will represent an increase in the construction costs, although the statement from section 2.1.1 relating to the entailed percentage of total costs can be applied to every one of the existing technologies.

In a near future, it is possible that manufacturers will be able to keep the promise made to be nearly cost neutral, and may some day even prove more cost-effective, but this is not the case today.

On the contrary, the technology that is more developed and more cost-effective nowadays is the use of batteries/super-capacitors or a combination of them for energy storage in the vehicle. The storage devices capture and hold energy, both from regenerative braking, from OCS wires where they are provided, and from charging stations, and use it where the OCS is not available. The size and weight of the energy storage device will be related to the amount of energy to store, and so, to the layout of the track and the vehicle's weight.

For these solutions, attention must be drawn to charging times, independence range, and maximum power allowed by the system.

These solutions have the additional advantage that they can be mounted in old vehicles and in the ones supplied by manufacturers that do not have this kind of technology. So, they are not so penalized by proprietary problems.

In general, it is important to note that the equipment that is not service proven can result in costly failures, train service delays, traffic disruptions, retrofits, equipment damage, or even employee or passenger injury. Nevertheless, proven-technologies are emerging that will be able to avoid overhead wires at least in the more sensitive areas of cities. This new advance can be the fact that propels the implementation of light rail networks in some reticent communities.

ACKNOWLEDGEMENTS

The author thanks the collaborations of cited manufacturers for their contribution with documentation about their systems.

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TABLE INDEX

Table 1: “Comparison between on-board energy storage devices”. Source: Modified from [6].

FIGURE INDEX

Figure 1: “a) Overhead contact wires in Tenerife’s light rail network (Spain). b) Miami’s street with electric wires close-up”.
Figure 2: “Alstom’s APS solution. a) General diagram. b) ETR detail”.
Figure 3: “Ansaldo’s TramWave system. a) ETR. b) Pick-up shoe. c) Diagram of pick-up process”.
Figure 4: “Bombardier’s PRIMOVE system. a) Technology base. b) Vehicle’s diagram”.
Figure 5: “CAF’s APR technology. a) LRV without ACR running under OCS. b) LRV without ACR braking. c) LRV with ACR running without OCS. d) LRV with ACR braking and accumulating energy in ACR modules. e) LRV with ACR accumulating energy in a zone with OCS”.

TABLE 1 Comparison between on-board energy storage devices. Source: Modified from [6]

STORAGE SYSTEM	Rate of charge	Life cycle cost	Life expectancy	Cost/Power storage	Power density/Weight	Safety
Super-capacitor	Very short charge	Medium	High	High	6 kWh/kg	High
Flywheel	Short charge time	Medium	Unknown	High	? (low)	Low – Not proved
Battery	Long charge time	Medium	Limited life	Low	30-160 kWh/kg	High

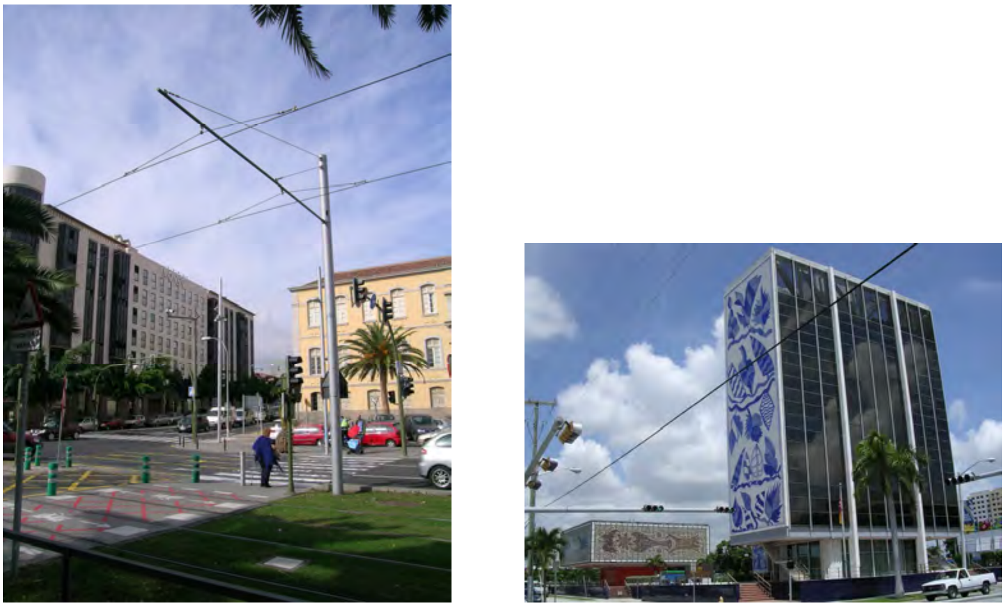


FIGURE 1 a) Overhead contact wires in Tenerife's light rail network (Spain). b) Miami's street with electric wires close-up.

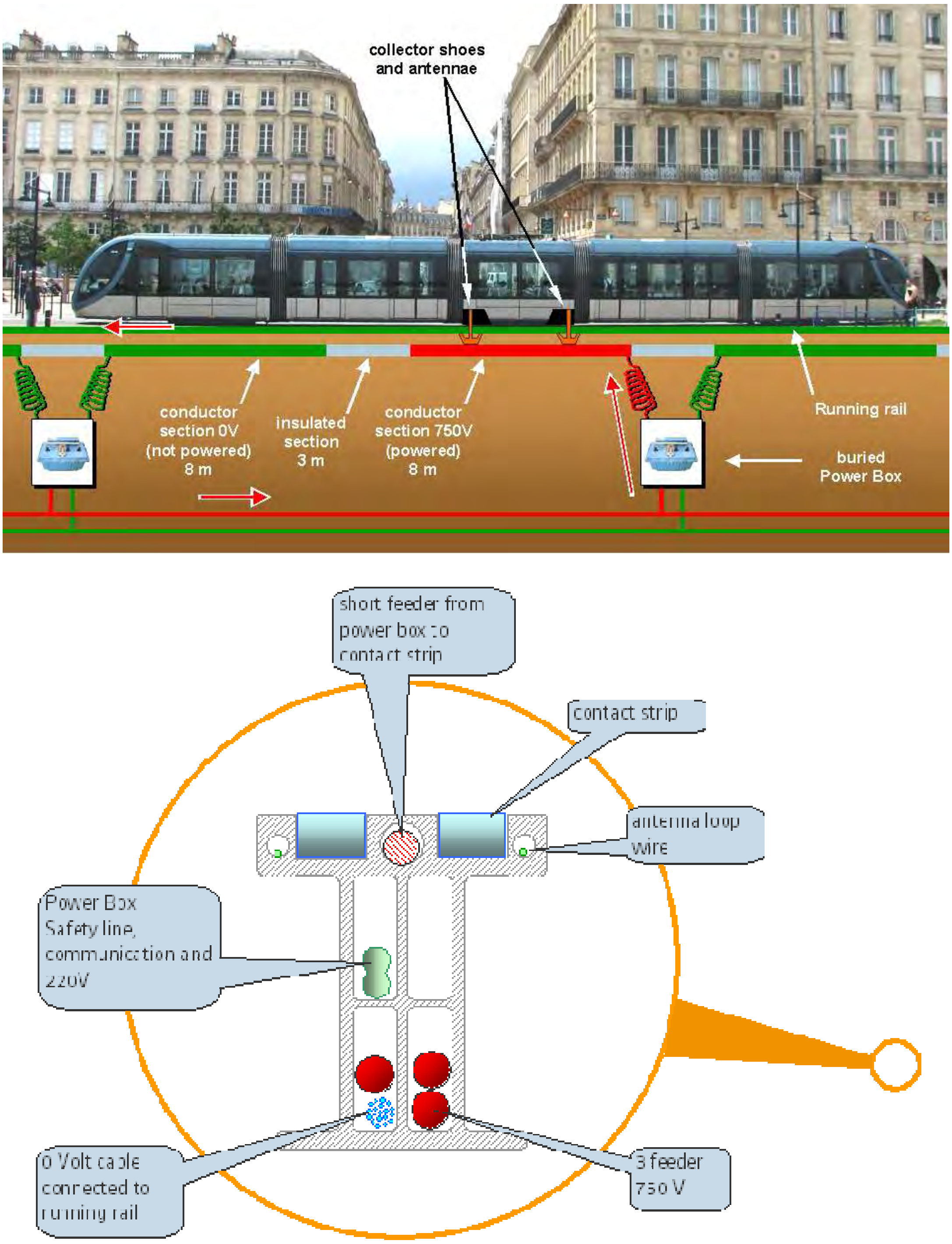

collector shoes and antennae
conductor section 0V (not powered) 8 m
insulated section 3 m
conductor section 750V (powered) 8 m
Running rail
buried Power Box
short feeder from power box to contact strip
contact strip
antenna loop wire
Power Box Safety line, communication and 220V
0 Volt cable connected to running rail
3 feeder 750 V

FIGURE 2 Alstom's APS solution. a) General diagram. b) ETR detail. Courtesy of Alstom.

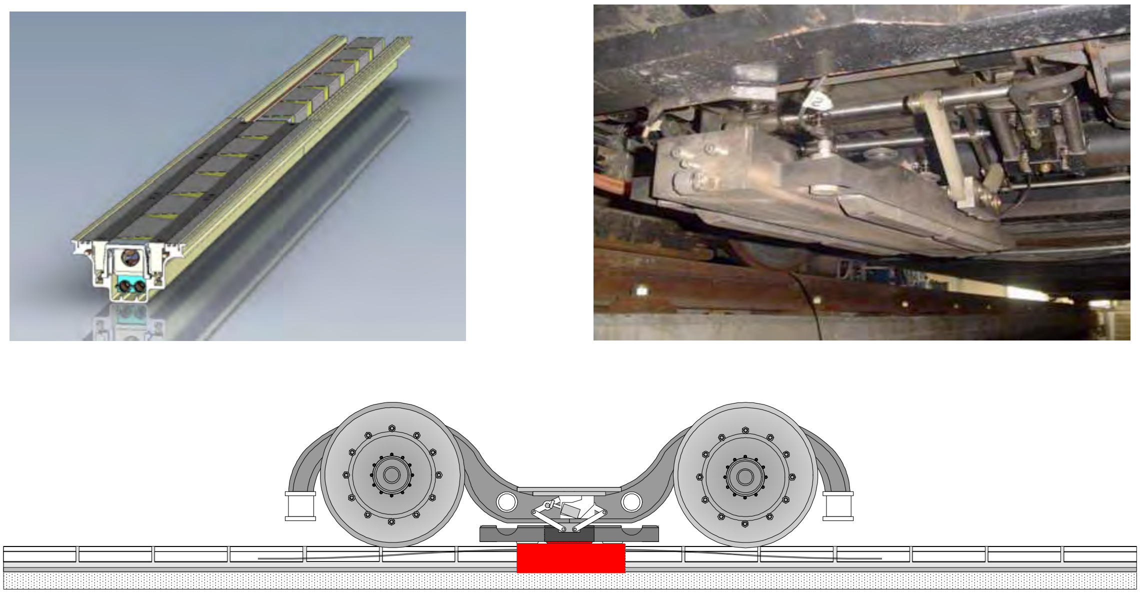


FIGURE 3 Ansaldo's TramWave system. a) ETR. b) Pick-up shoe. c) Diagram of pick-up process. Courtesy of Ansaldo.

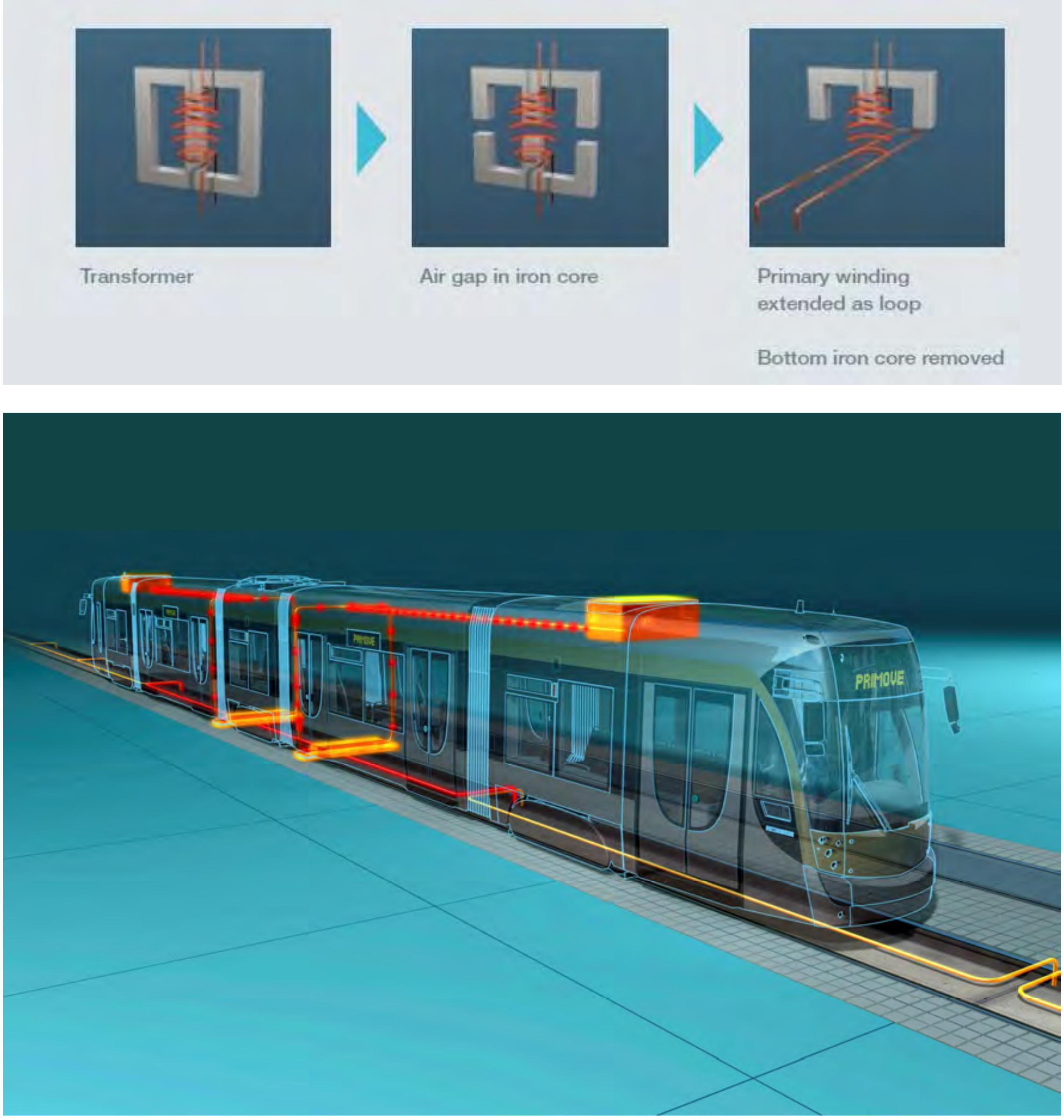


FIGURE 4 Bombardier's PRIMOVE system. a) Technology base. b) Vehicle's diagram. Courtesy of Bombardier.

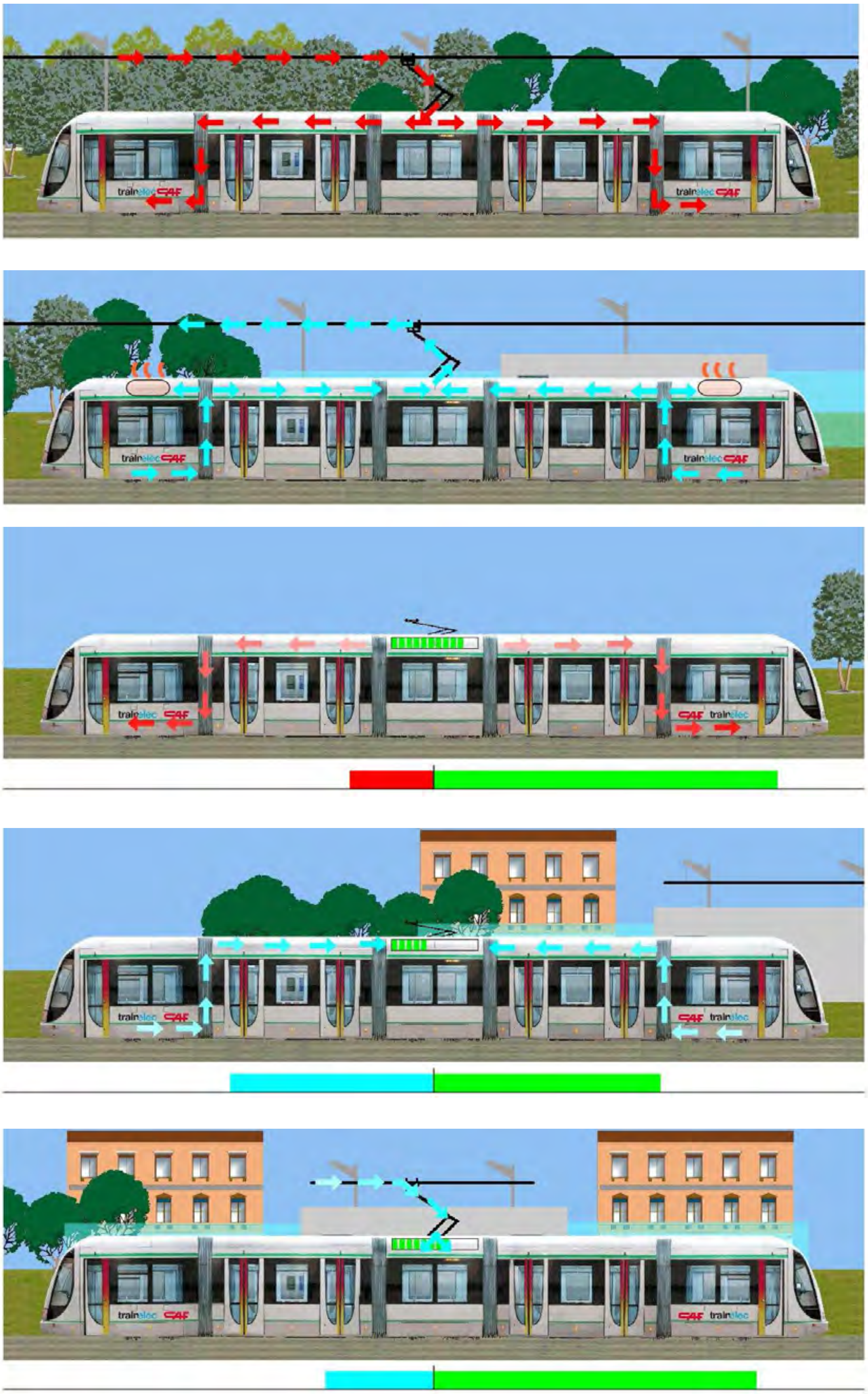


FIGURE 5 CAF's APR technology. a) LRV without ACR running under OCS. b) LRV without ACR braking. c) LRV with ACR running without OCS. d) LRV with ACR braking and accumulating energy in ACR modules. e) LRV with ACR accumulating energy in a zone with OCS. Courtesy of CAF.

Streetcar Propulsion Power: Alternatives and Considerations

APTA Streetcar and Heritage Trolley Subcommittee

James H. Graebner, Chair
T.R. Hickey, AICP, Vice Chair
Timothy R. Borchers, Secretary / Technologist
James D. Schantz, Communications / History
Martin P. Schroeder, P.E., Chief Engineer, APTA

Public Meeting
Hosted by: DC Surface Transit, Inc.
Renaissance Hotel
Washington, DC

May 6, 2010

Introduction:

American Public Transportation Association

- Leading Force in Advancing Public Transportation Since 1882
- Legislation
- Conferences – Over 20 a year
- Education and Training
- Committee Activities
- Standards Development
- Data Collection and Dissemination
- Scientific Research

APTA's Approach

- Neutral
- Apply Industry Experience
- Utilize our Experts within the Streetcar Subcommittee
  - James H. Graebner, Chair
  - Thomas Hickey, Vice Chair
  - Tim Borchers, Secretary & Technology
  - James Schantz, History and Data

Presentation Outline

- Streetcar Overview
- Conventional Power Systems
- Alternative Power Systems
- Energy Storage Technology
- Implementation and Operation
- Summary

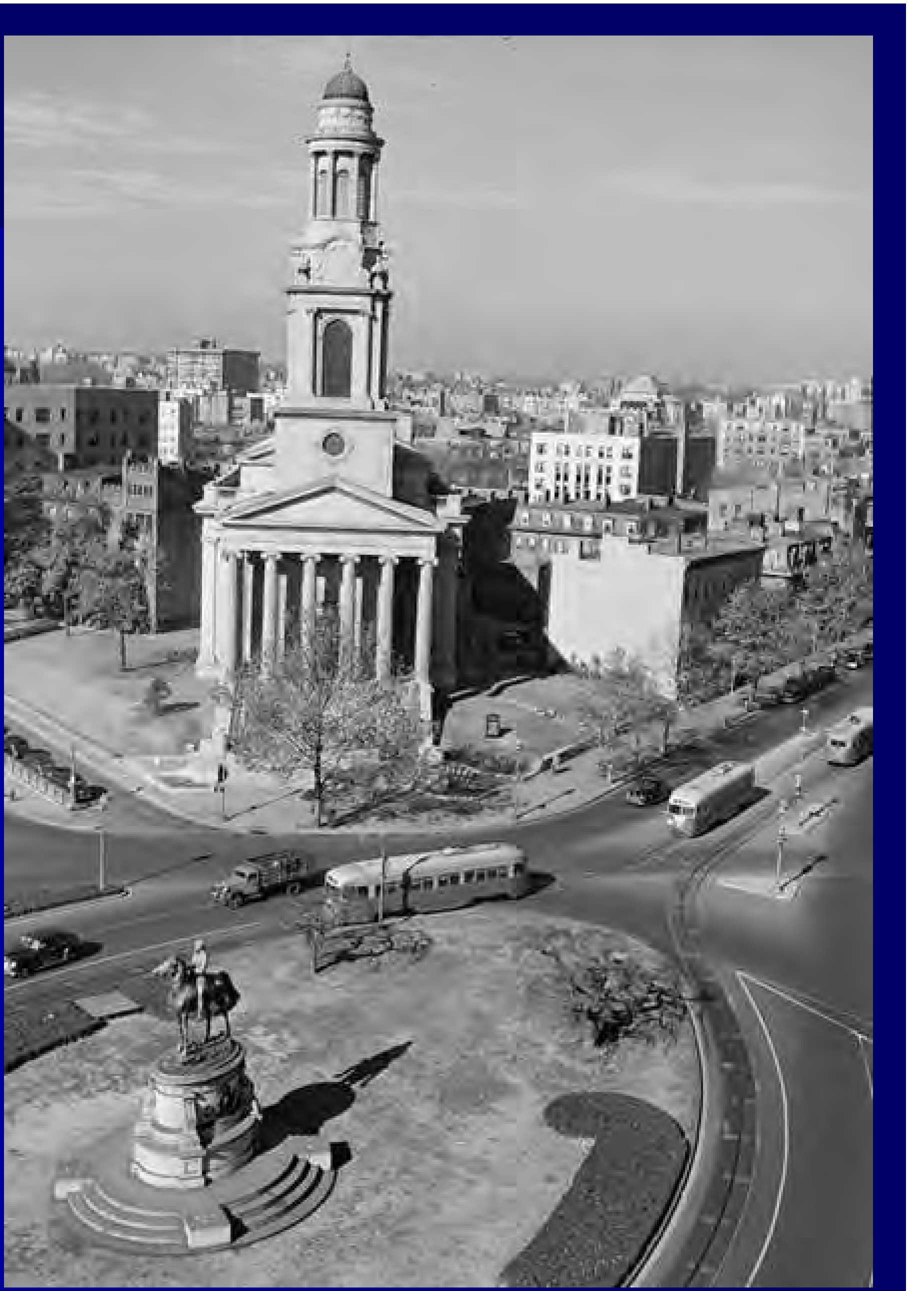
Streetcar Overview

James H. Graebner

Chair, APTA Streetcar and Heritage Trolley Subcommittee
President, Lomarado Group
Denver, Colorado

DC Streetcars

- 1862 – 1962
  Streetcar Era
- 1888 – 1895
  Technology
  Turmoil



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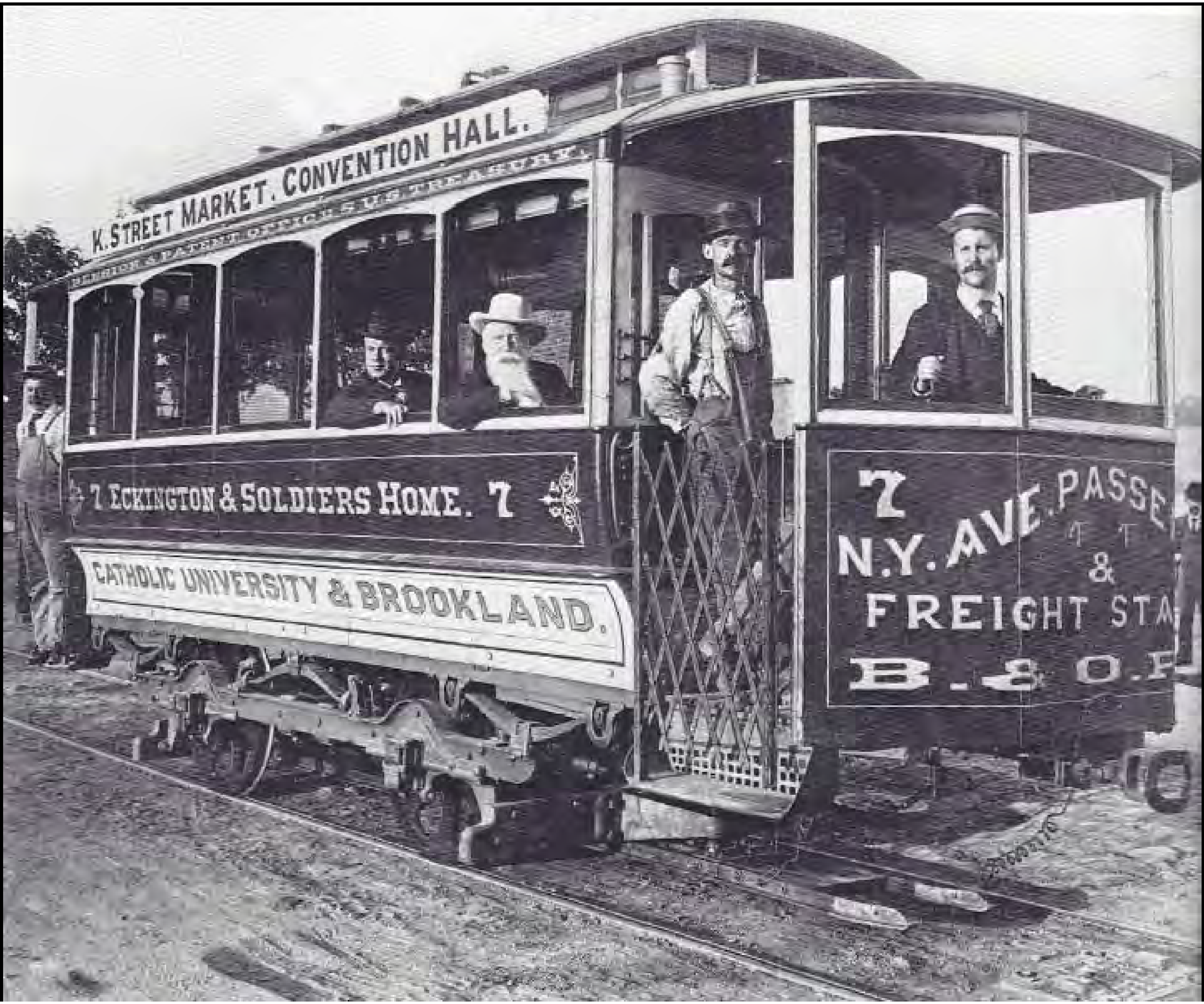
WASHINGTON & GEORGETOWN R.R.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7 ECKINGTON & SOLDIERS HOME. 7
CATHOLIC UNIVERSITY & BROOKLAND.
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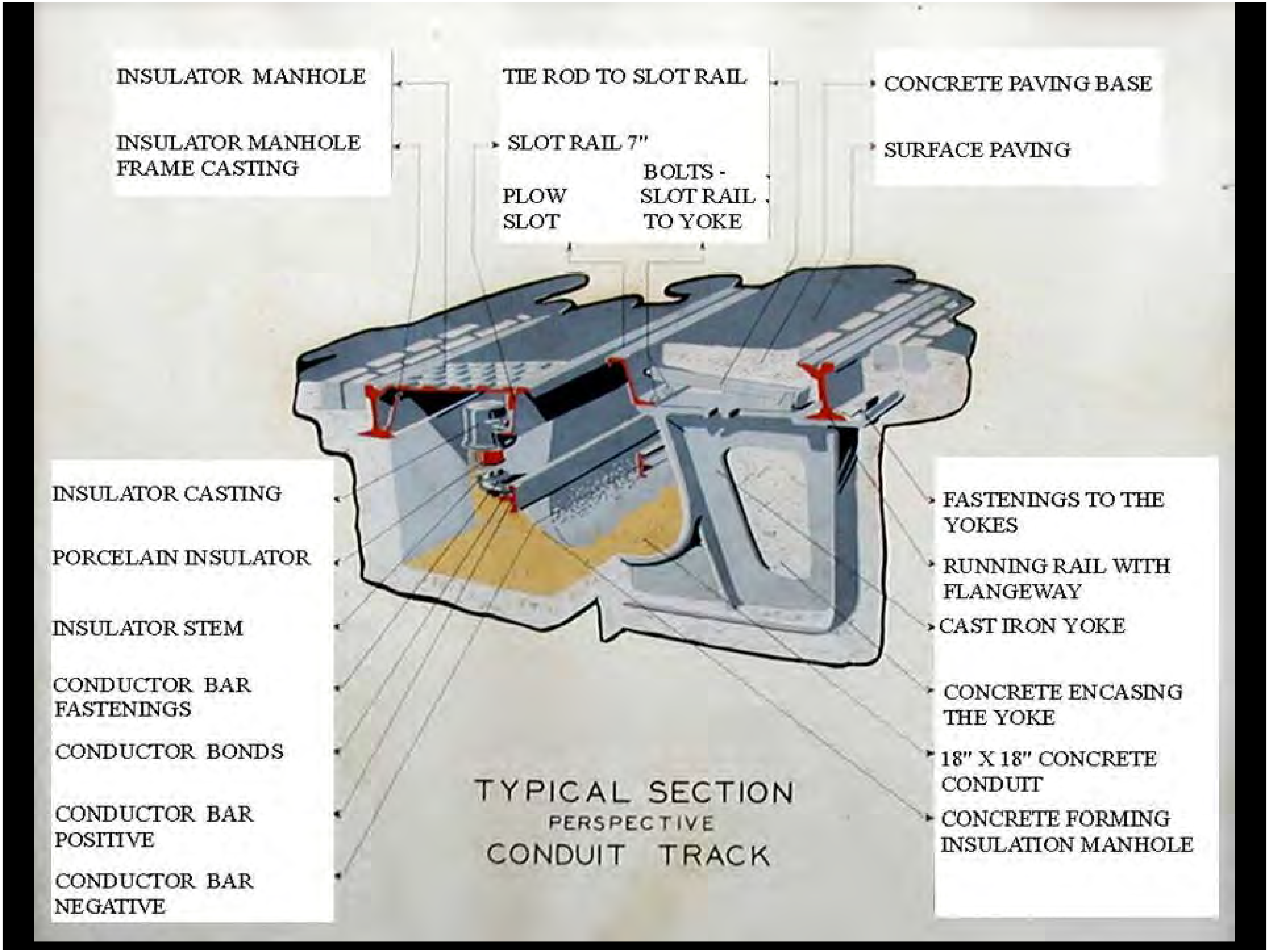
N.Y. AVE. PASSE
&
FREIGHT STA
B. & O. F



TYPICAL SECTION
PERSPECTIVE
CONDUIT TRACK

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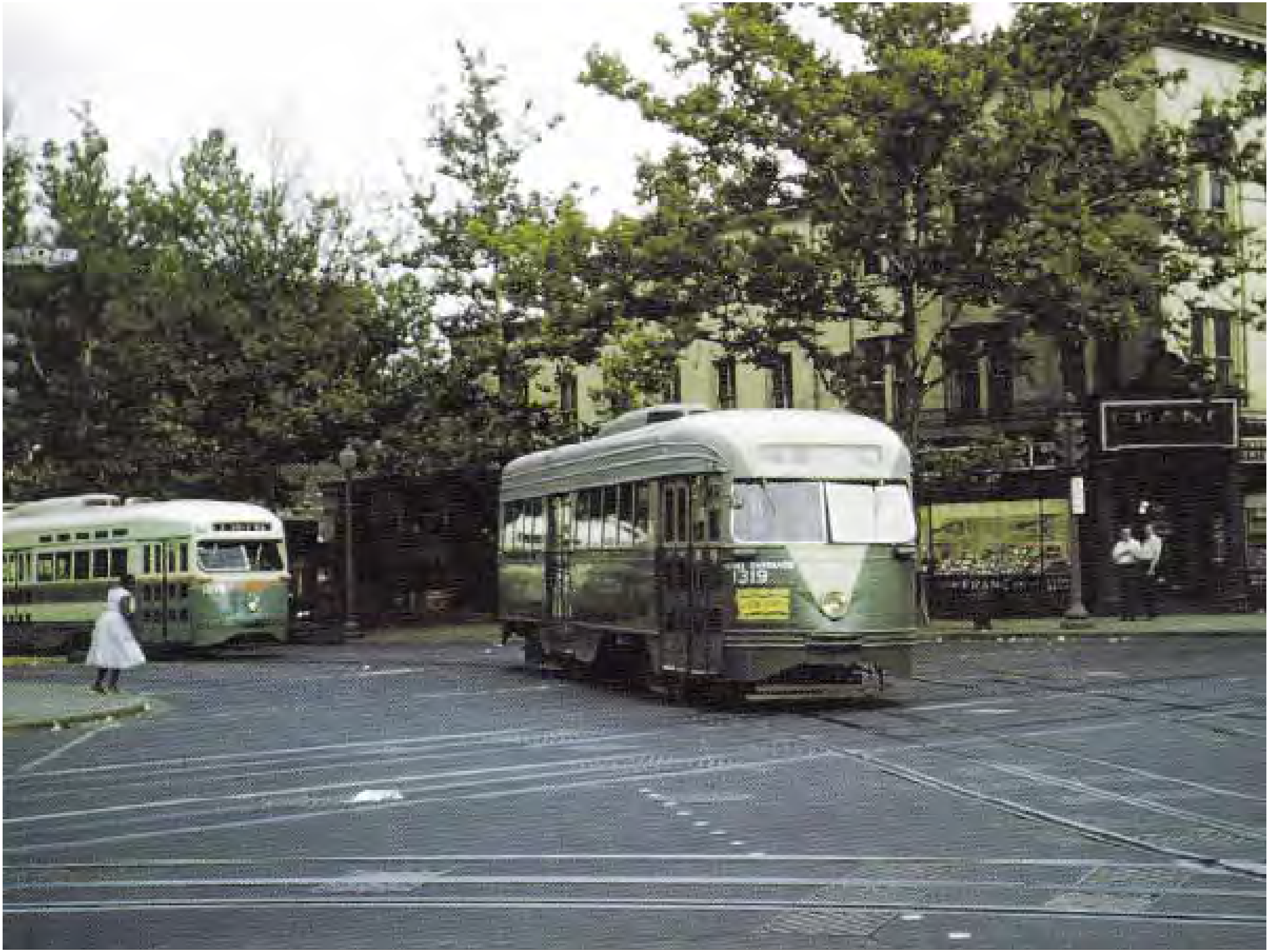
303
THE CAPITAL TRACTION CO



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DC Streetcars – *Then and Now*

The fundamentals remain the same despite outward changes in appearance and upgrades in technology.

Streetcar Power Systems

- External power supply or generated on-board
- Continuous or not
  - If not continuous, on-board storage system is needed

Which approach (or combination of approaches) best suits the needs of the District?

Conventional Power Systems

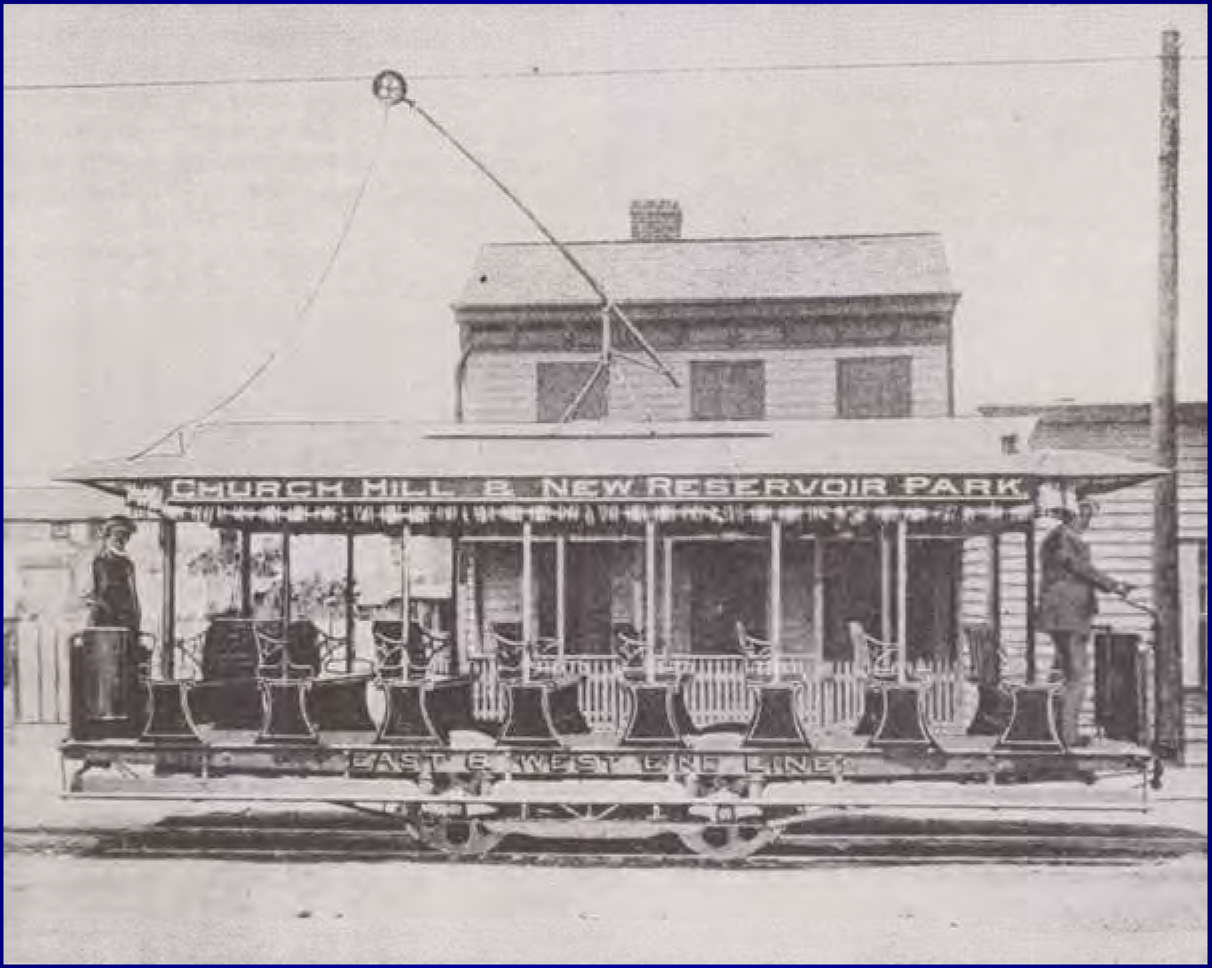
James D. Schantz

APTA Streetcar and Heritage Trolley Subcommittee
Chairman, Board of Trustees
New England Electric Railway Historical Society
Kennebunkport, Maine

19th Century: Experimentation

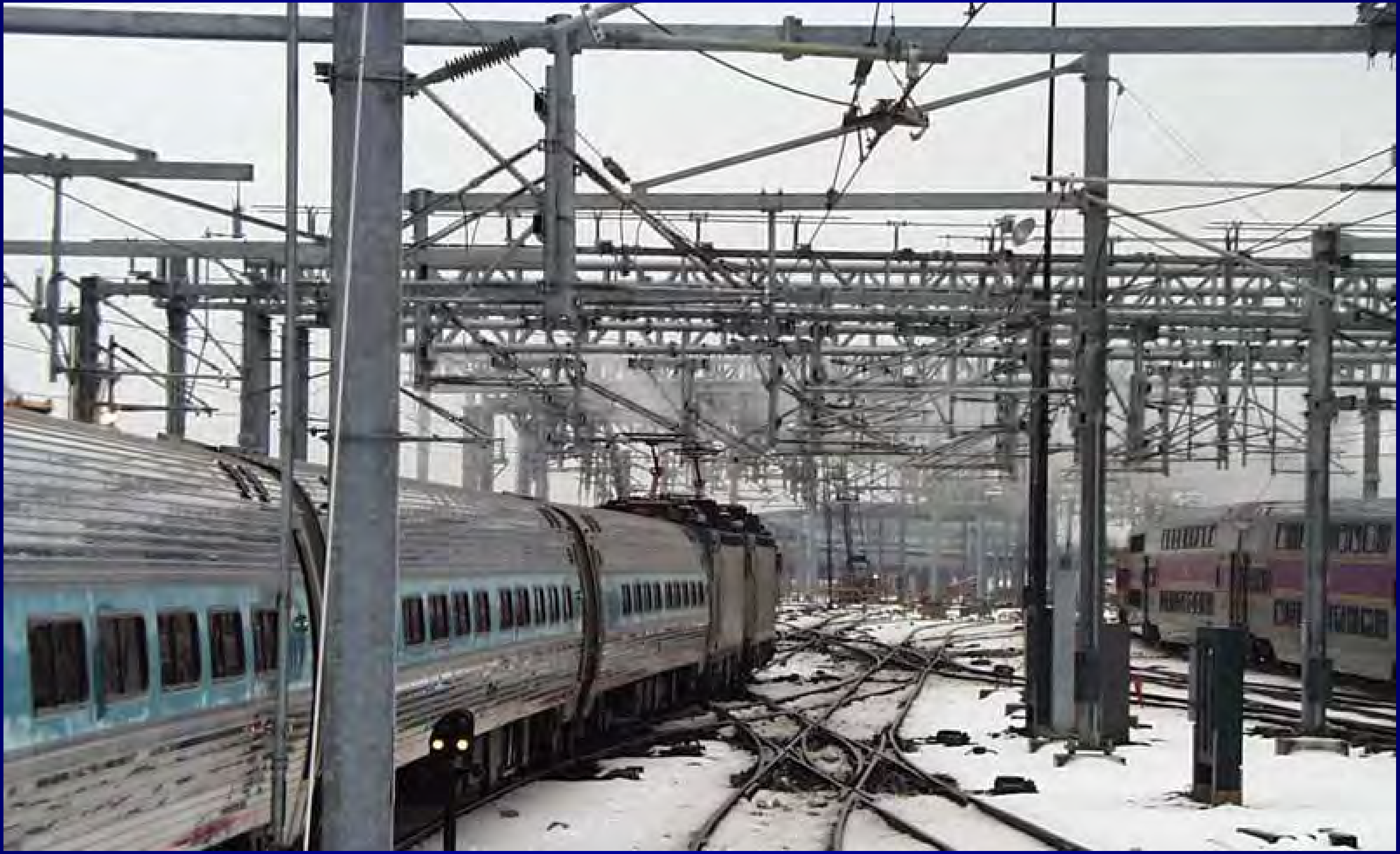
WASHINGTON. DAY. CONE STS. LINCOLN AV & SCOTLAND ST
CROSSTOWN LINE
5
5
R.R. DEPOTS, CEMETERY, MUSIC HALL

19th Century: Success



20th Century: Standard Practice

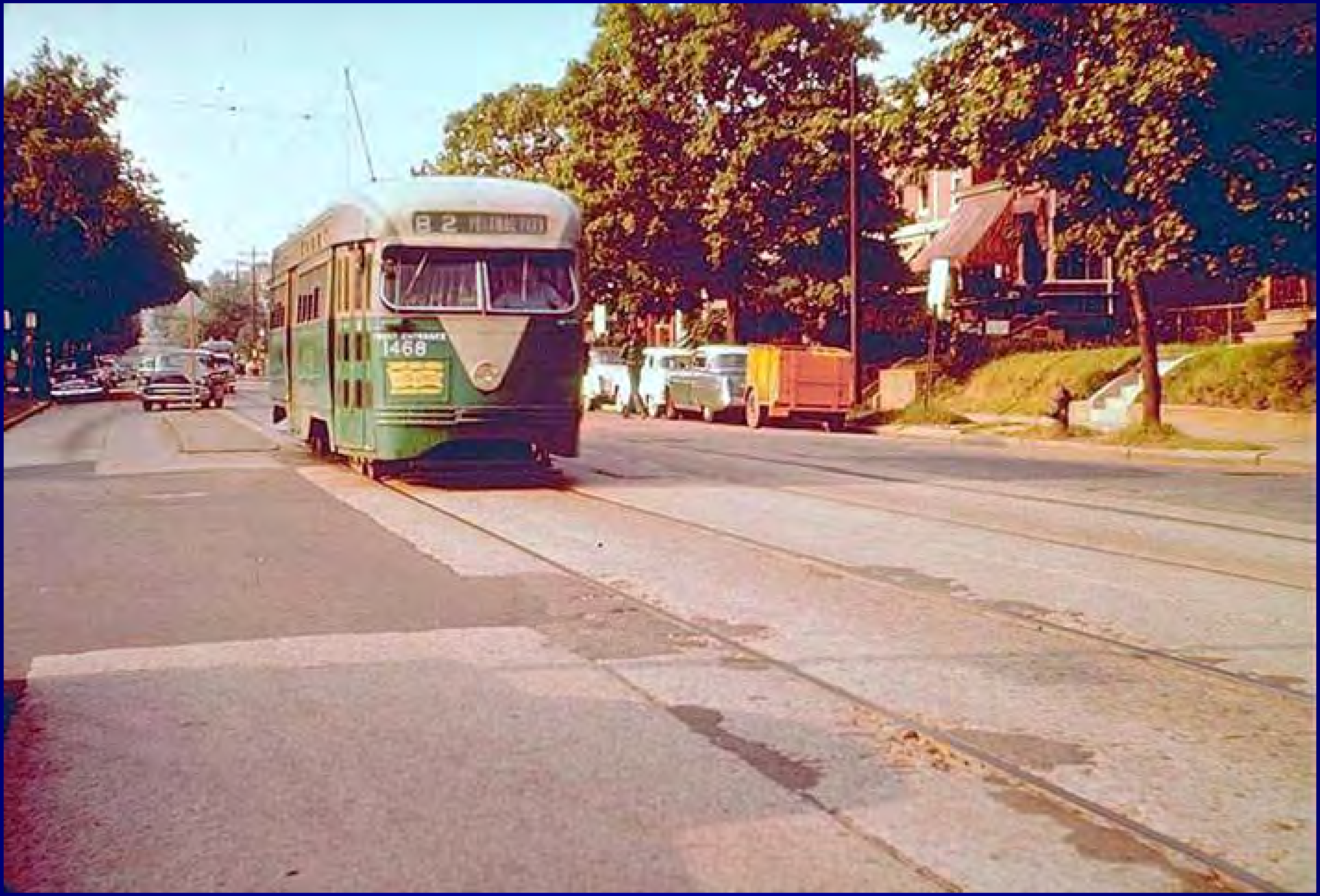
Trolley Wire: What is is *not*...



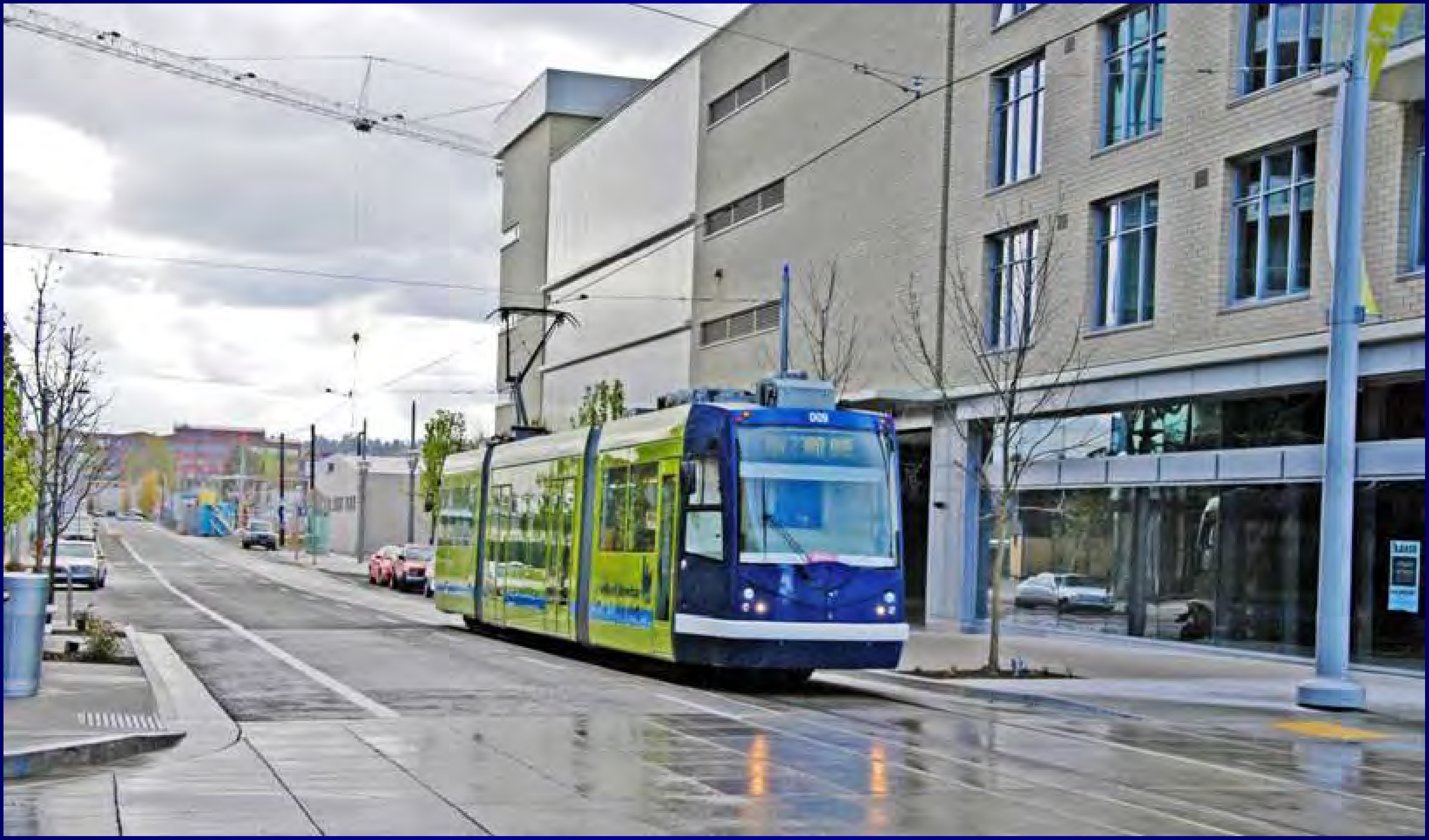
Trolley Wire: What it is *not*...

Trolley Wire: What it *is*...

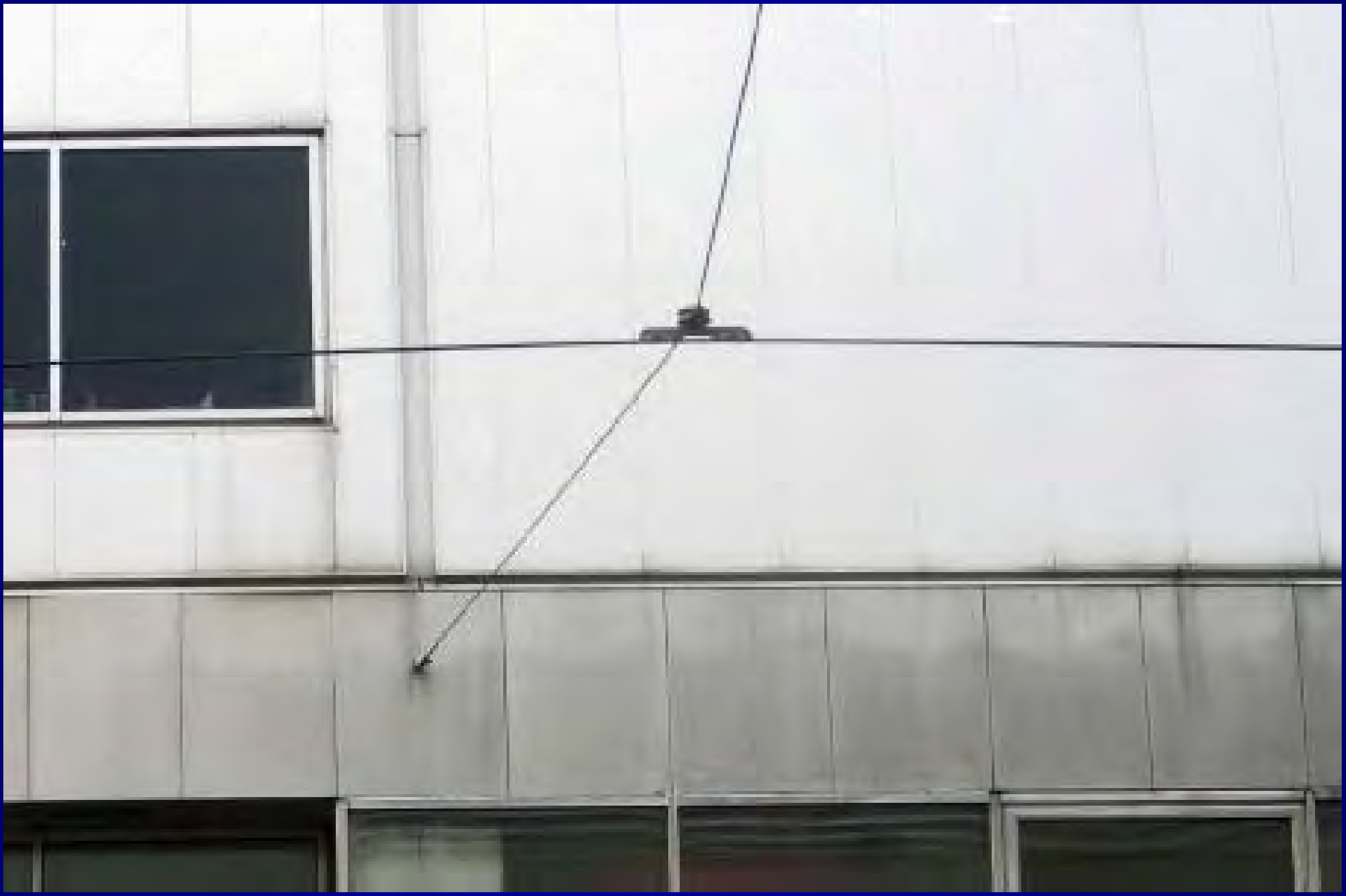
Trolley Wire: Poles and Spans



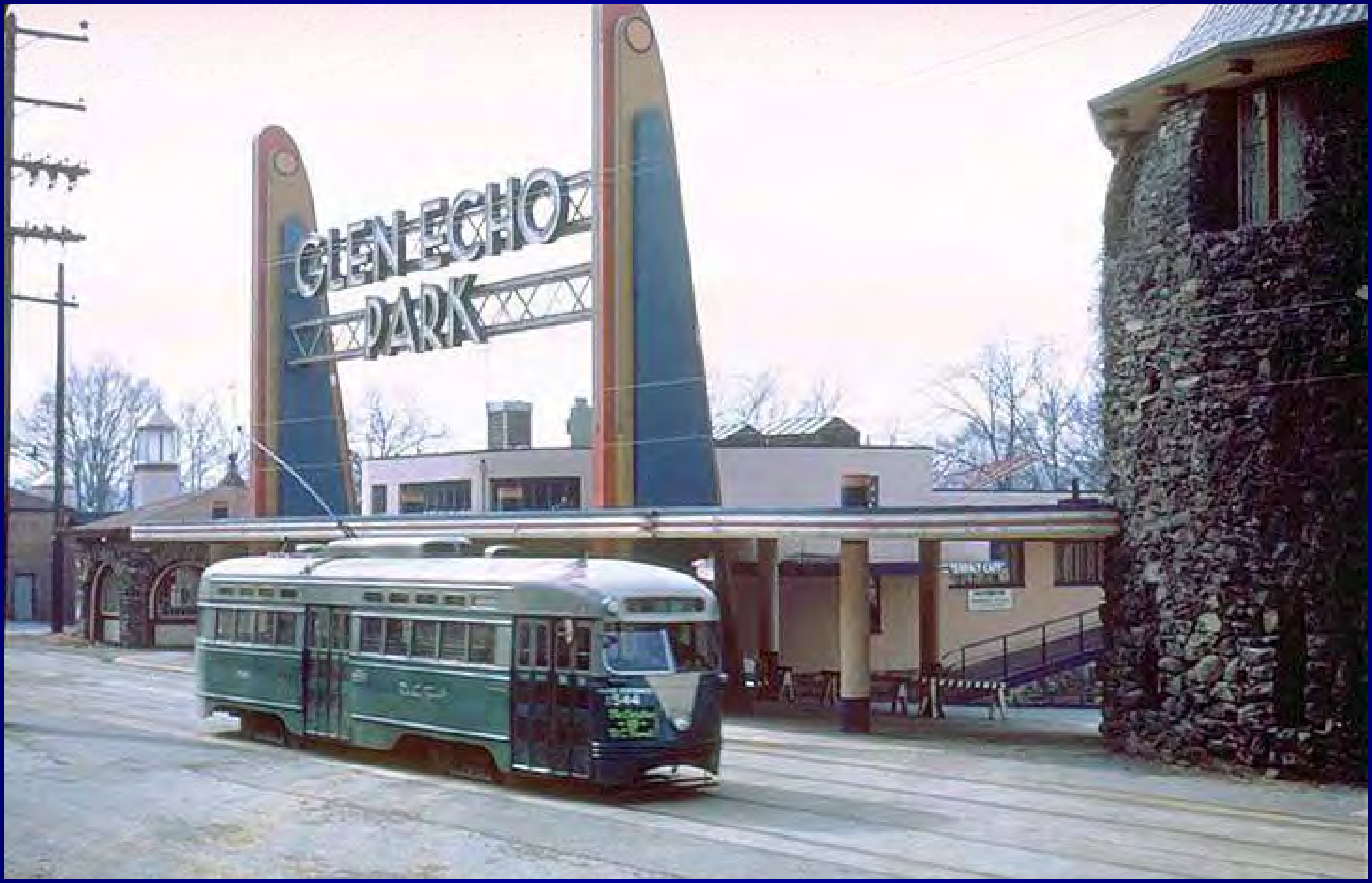
Trolley Wire: Poles and Spans



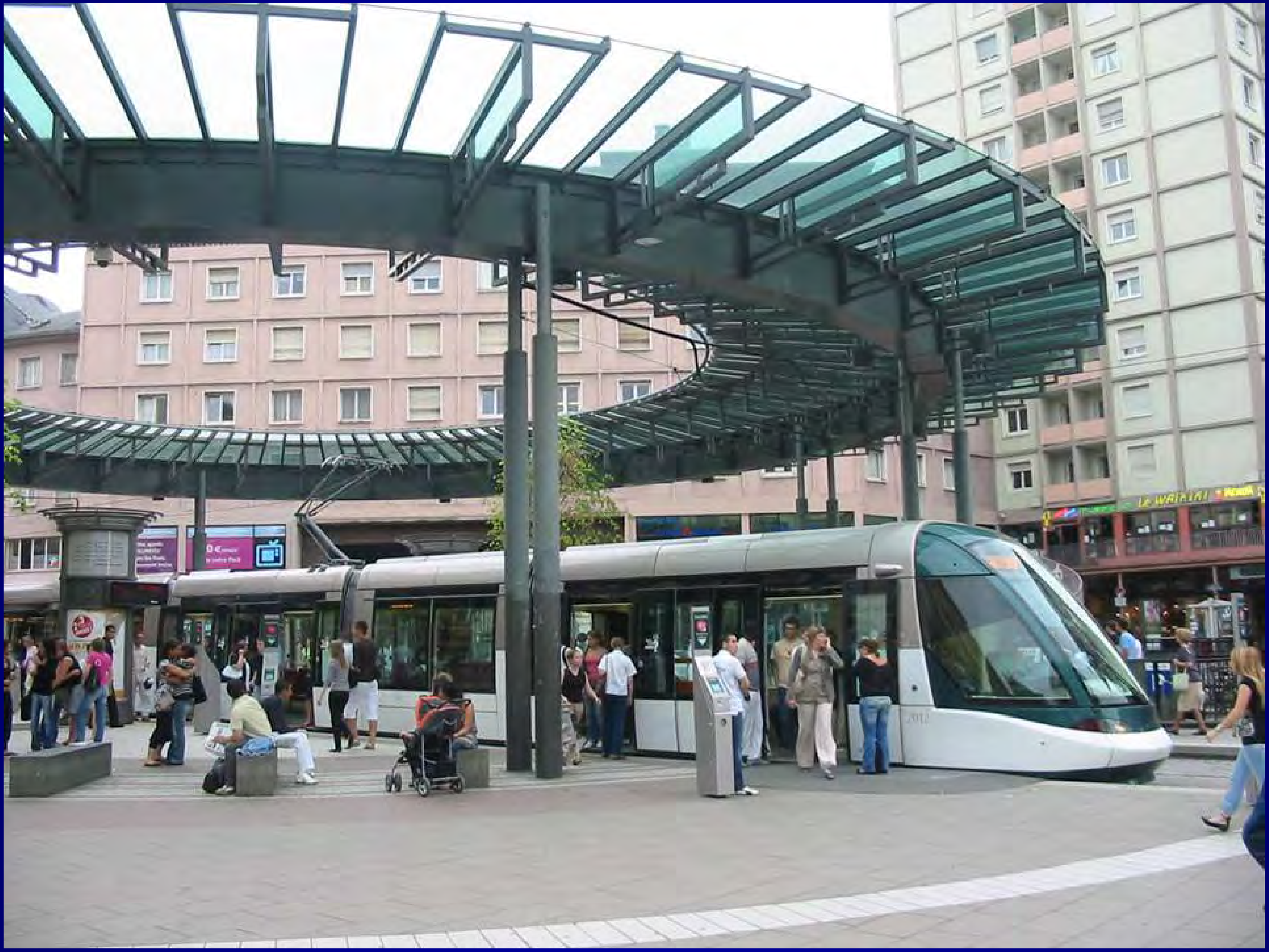
Trolley Wire: Building Anchor



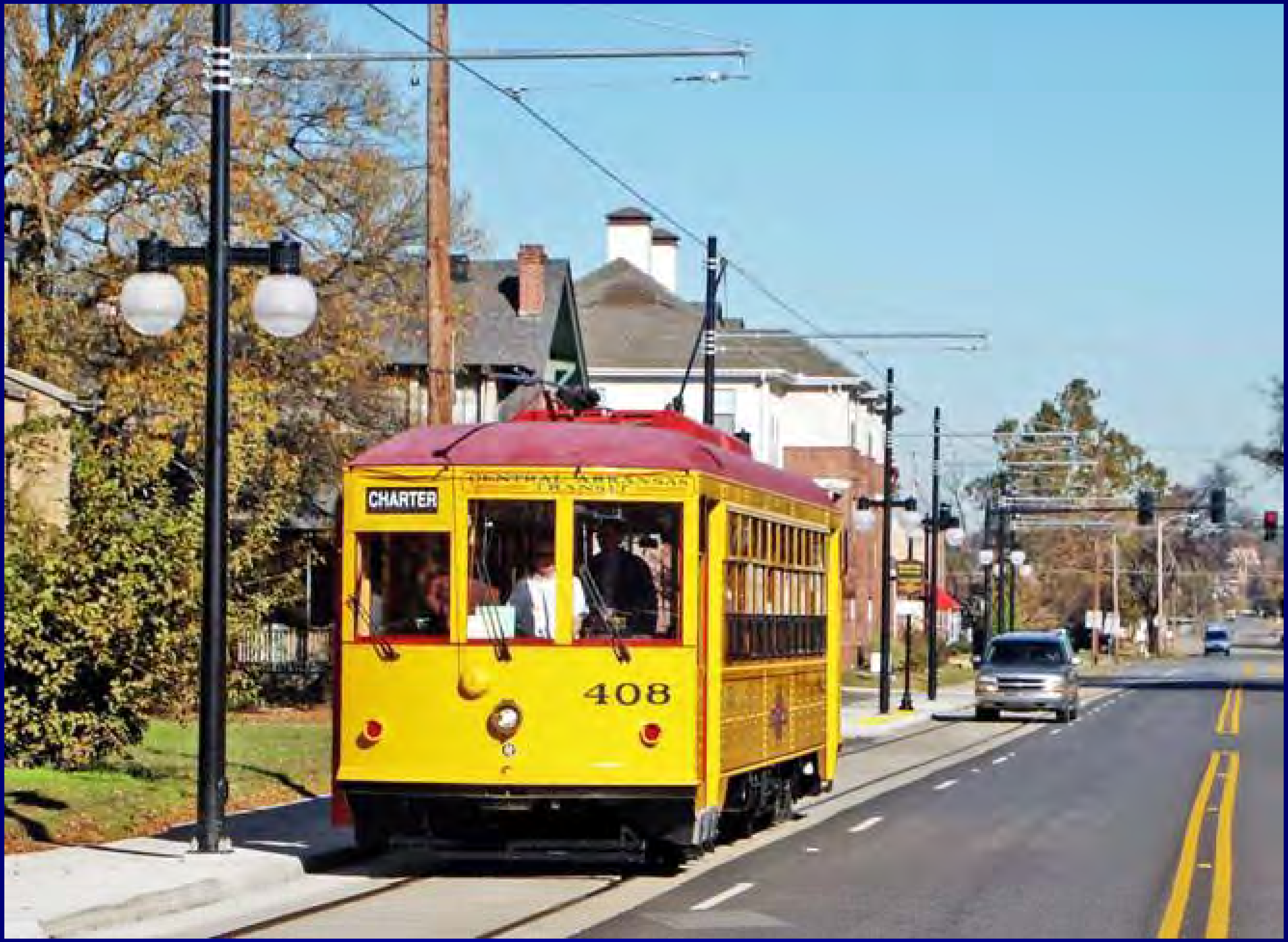
Trolley Wire: Building Anchor



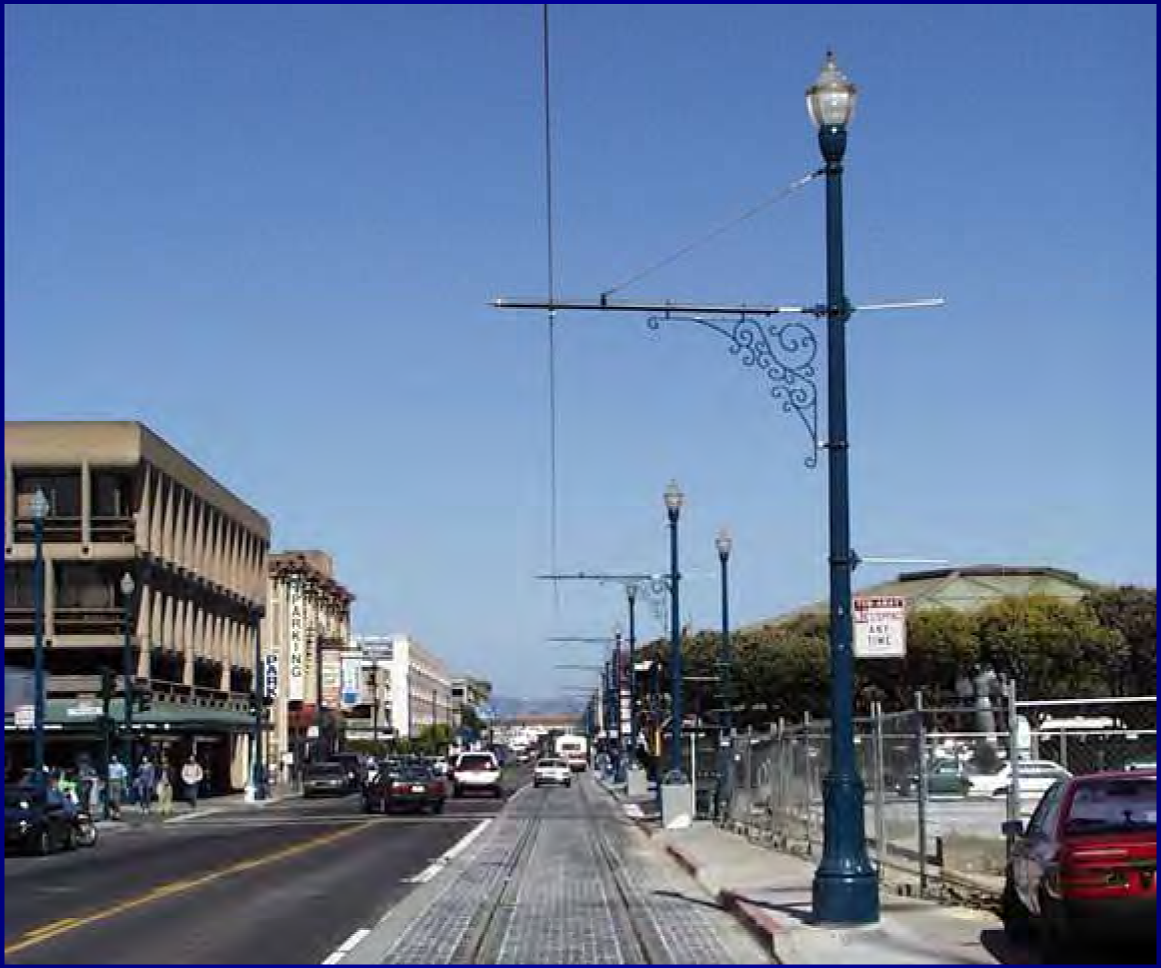
Trolley Wire: Building Anchor



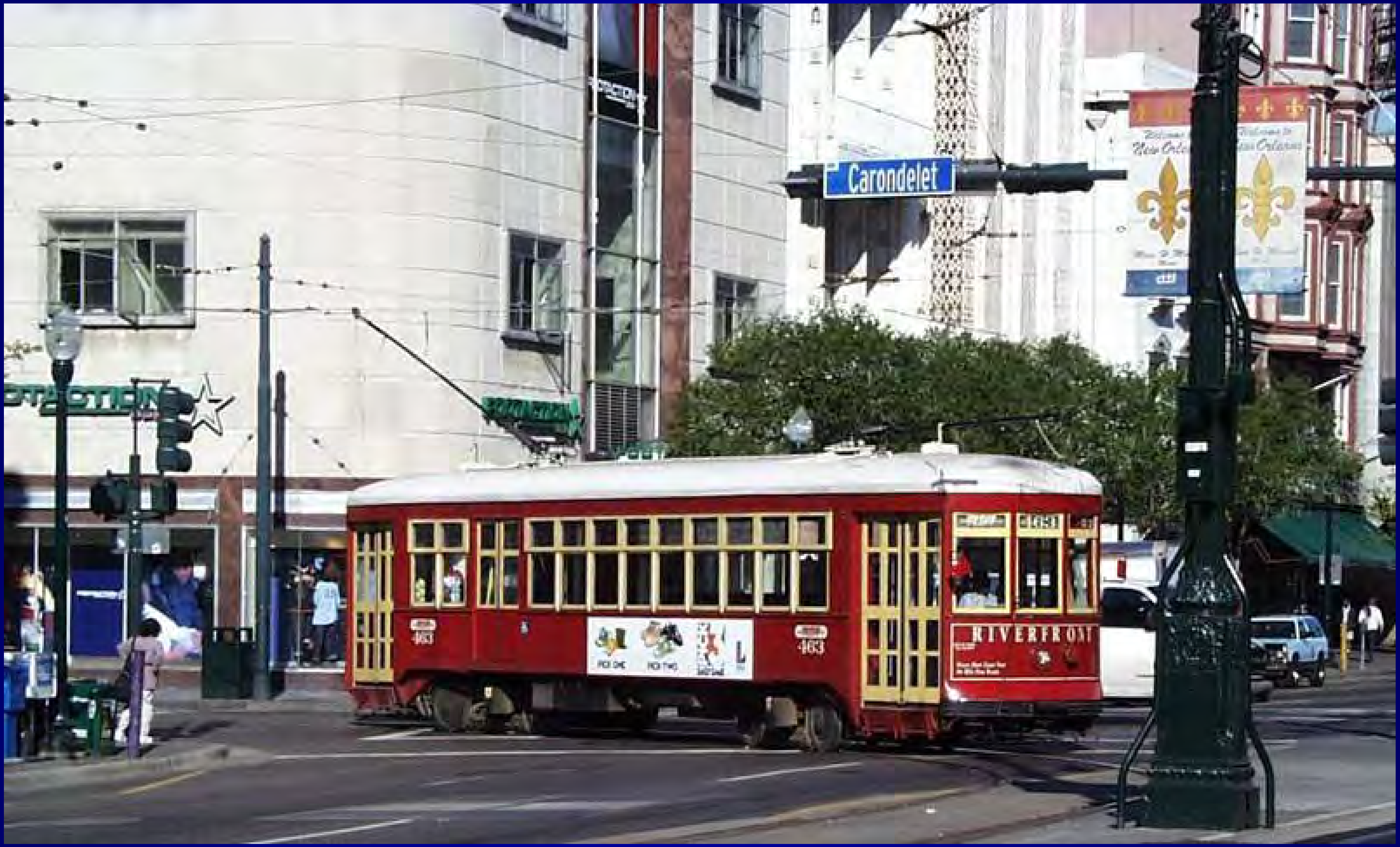
Trolley Wire: Bracket Arm



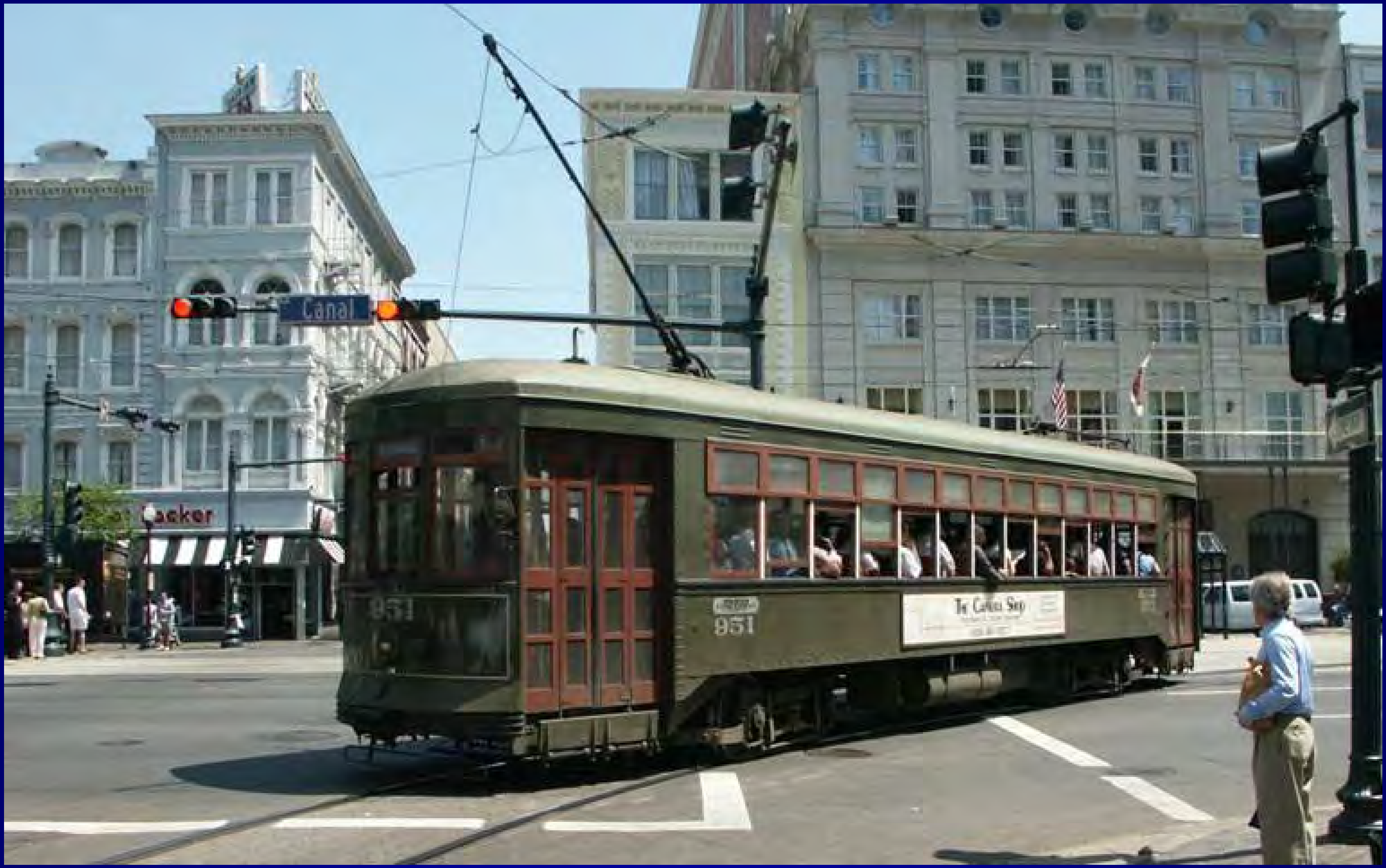
Trolley Wire: Bracket Arm



Trolley Wire: Curves



Trolley Wire: Curves



Trolley Wire: Summary

- Used for 120 years around the world
- Inexpensive to build and maintain
- Half inch diameter, 18 feet up
- Visual intrusion can be minimized

Conduit: Only Widely Used Alternative

Conduit: Only Widely Used Alternative

Alternative Power Systems

Timothy R. Borchers

APTA Streetcar and Heritage Trolley Subcommittee
Principal, City Rail Solutions
Tampa, Florida

Alternatives to Overhead Contact System (OCS)

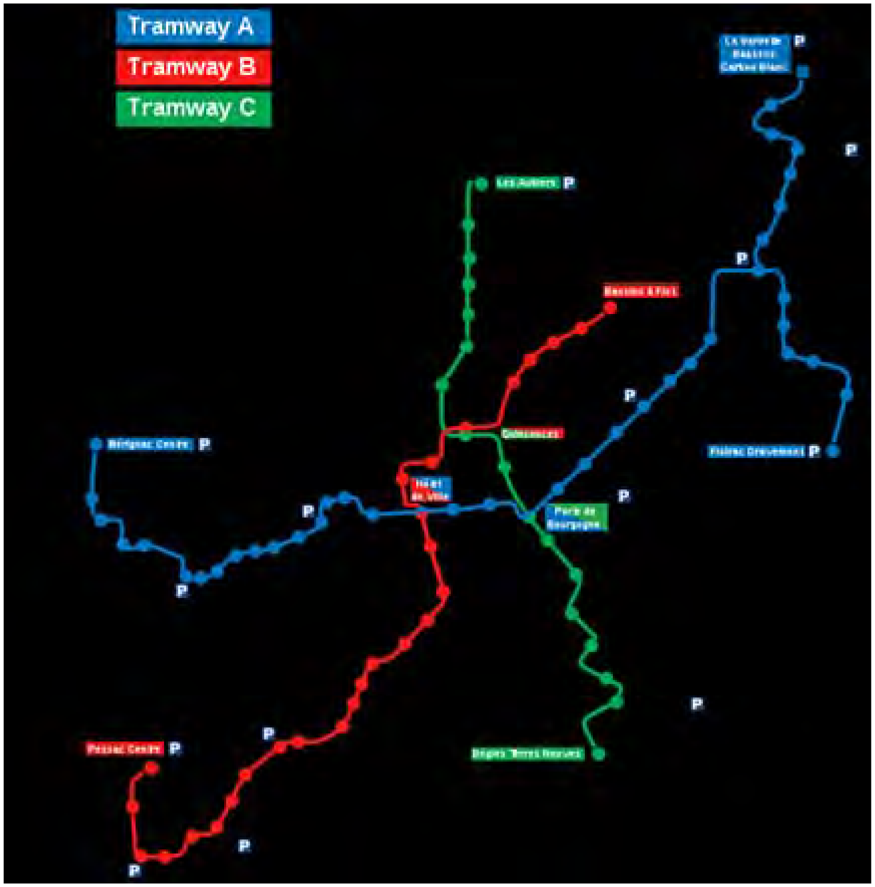
- Ground level power supply.
- On-board electric energy storage (batteries, flywheels, super or ultra capacitors)
- On-board electric energy generation (internal combustion engine, fuel cell)

*Ground Level Power Supply Innorail/APS

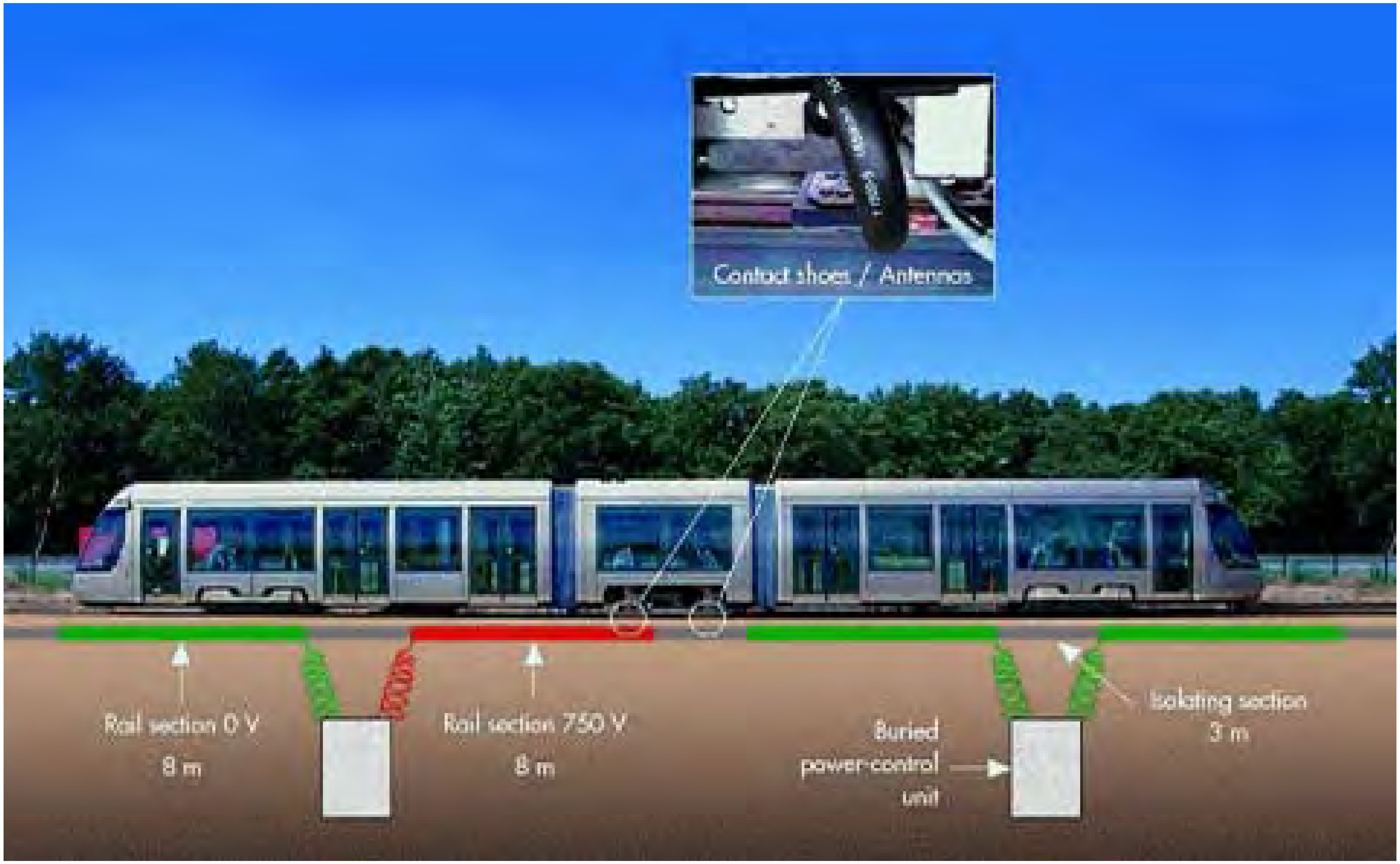
Ground Level Power Supply Innorail/APS

- Bordeaux France
- Daily ridership 165,000
- Total system length 43 km (27 mi)
- 12 km of APS
- 74 Citadis trams

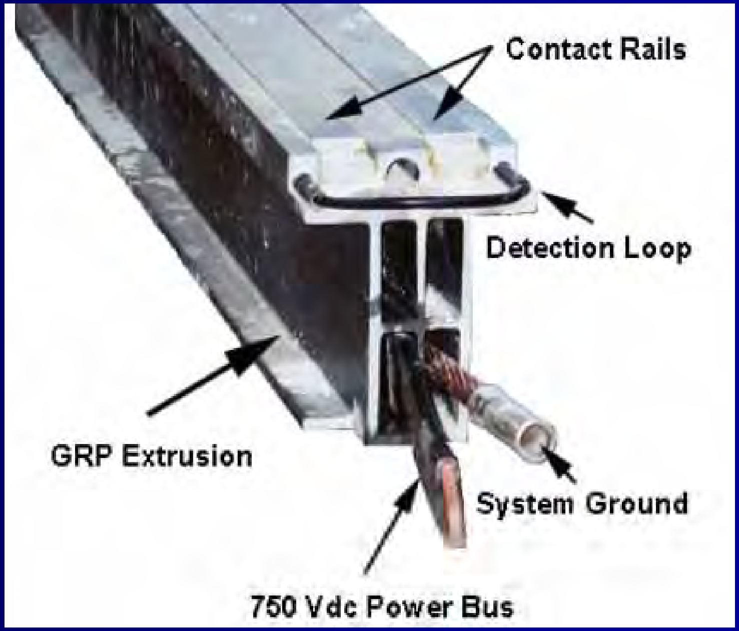
The Alstom Innorail or Ground-level power supply, is also known as surface current collection and Alimentation par Sol (APS)

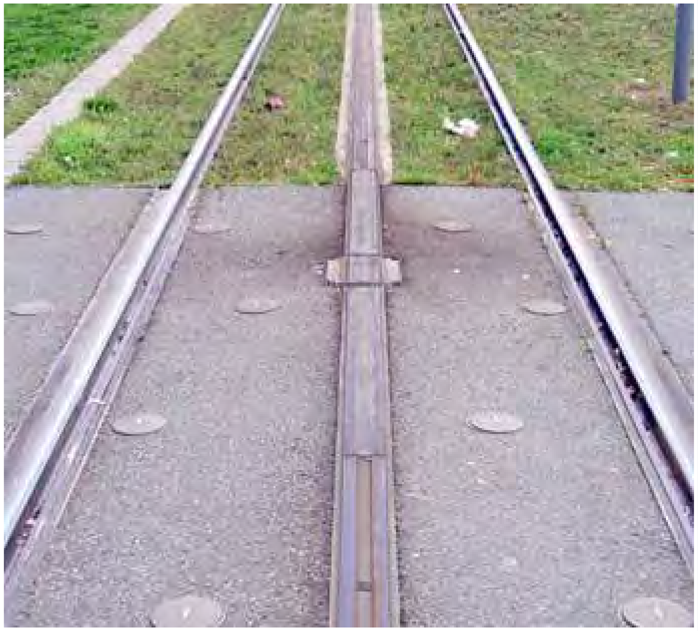


Ground Level Power Supply Innorail/APS



Ground Level Power Supply Innorail/APS





The system had a number of “teething” problems, poor drainage and debris on the contact strips caused service unreliability. Reliability has improved and one kilometer of surface contact replaced with OCS. Reliability under heavy ice and snow conditions has not been established.

Ground Level Power Supply Innorail/APS

Ground Level Power Supply Innorail/APS

HOTE
BANQUE CLAVERIE

Ground Level Power Supply Innorail/APS

- Sources suggest that in Europe APS adds about US $130,000 to the cost of each tram, while the infrastructure is about 300% more expensive than overhead wires.
- Several new French and European tram systems will use APS over part of their networks.
- The planned Al Sufouh Tramway in Dubai will use APS exclusively.

*Ground Level Power Supply - Primove

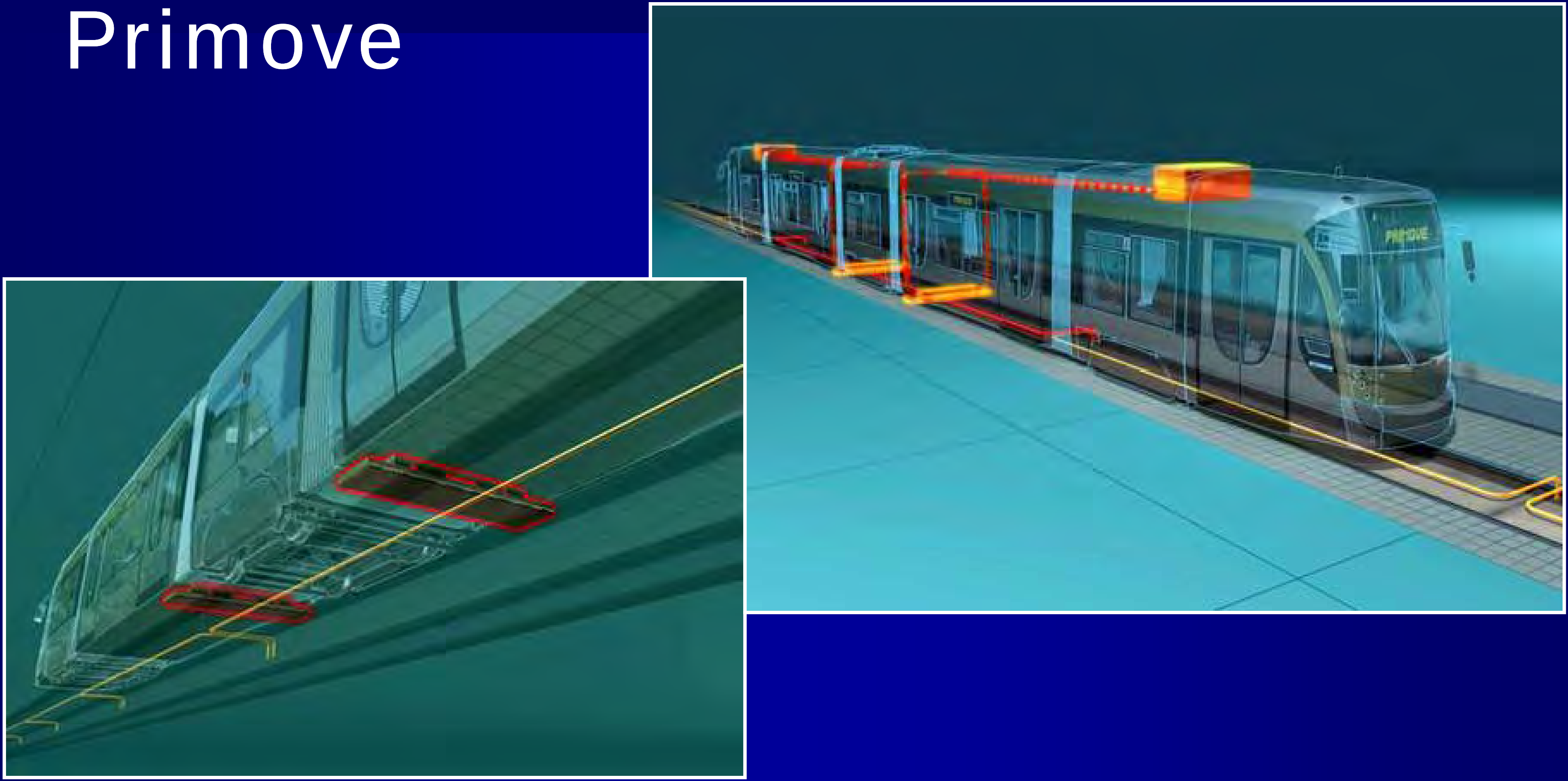
Primove was unveiled by Bombardier on Jan. 2 2009.

It uses a magnetic field to transmit power from a circuit built into the track to pick-up coils beneath a tram. These coils transforms the magnetic energy into electricity which charges super capacitors on the tram.

The in-ground equipment is energized only when covered by the vehicle. The prototype provided sufficient power for a 98-ft.-long (30 meter) LRV operating at 25 mph (40 kph) on a six-percent grade.

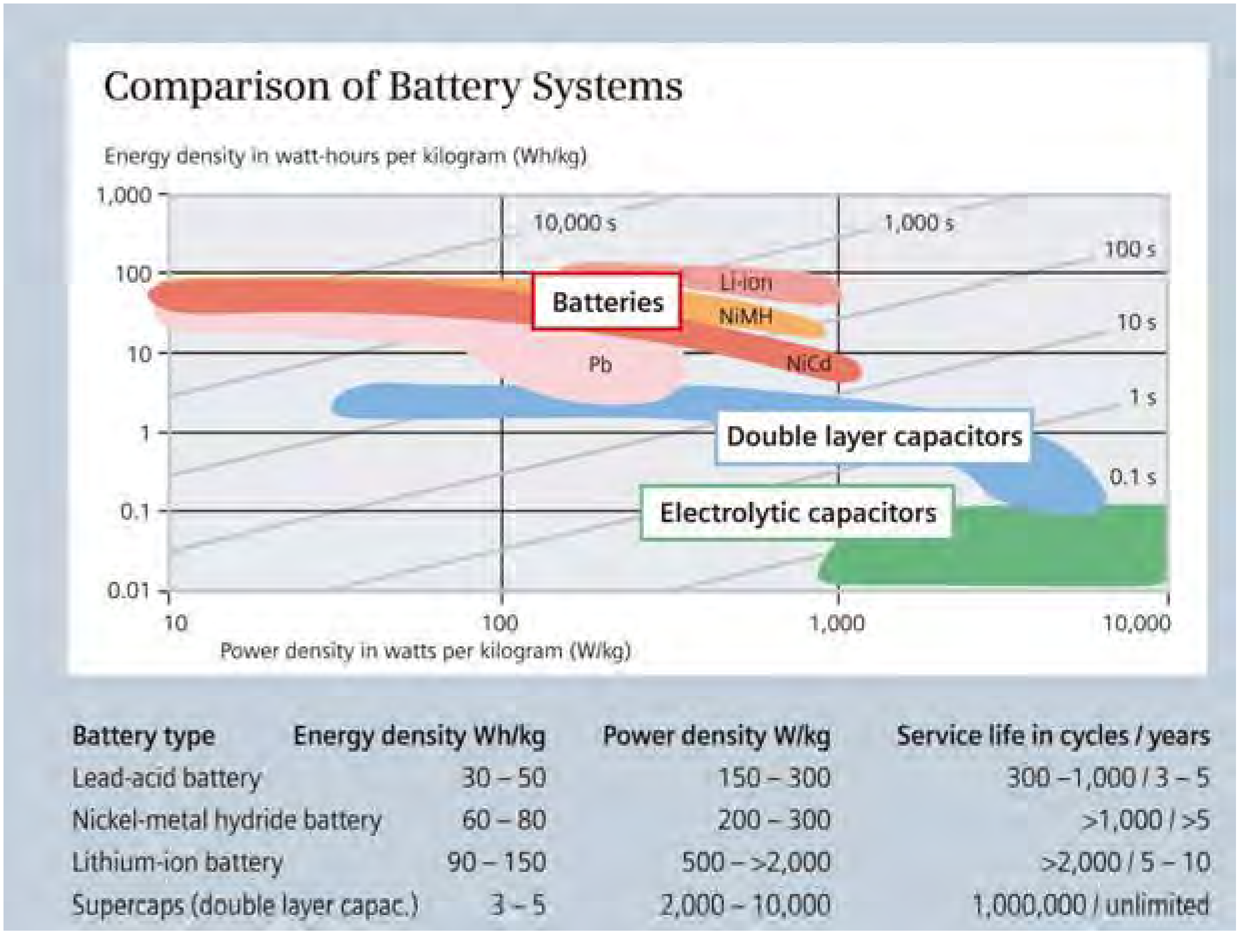
Bombardier Primove market-ready in 2010.

Ground Level Power Supply - Primove



Using inductive power to charge super capacitors to power the tram.

On-board electric energy storage (batteries, flywheels, super capacitors)

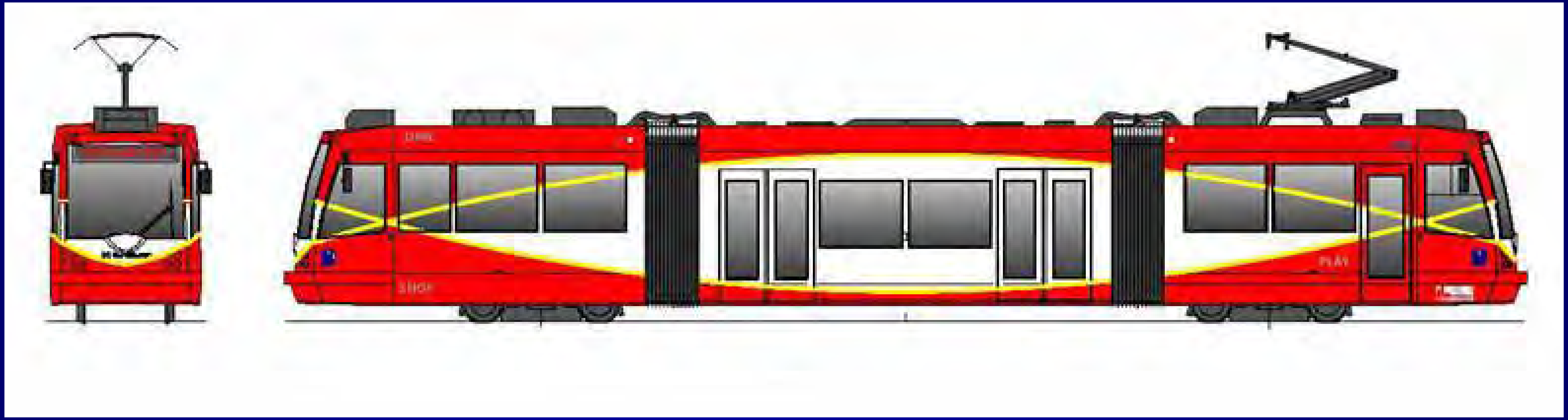


Comparison of Battery Systems

Battery type	Energy density Wh/kg	Power density W/kg	Service life in cycles / years
Lead-acid battery	30 – 50	150 – 300	300 –1,000 / 3 – 5
Nickel-metal hydride battery	60 – 80	200 – 300	>1,000 / >5
Lithium-ion battery	90 – 150	500 – >2,000	>2,000 / 5 – 10
Supercaps (double layer capac.)	3 – 5	2,000 – 10,000	1,000,000 / unlimited

*On-board electric energy storage batteries - Trio Streetcar

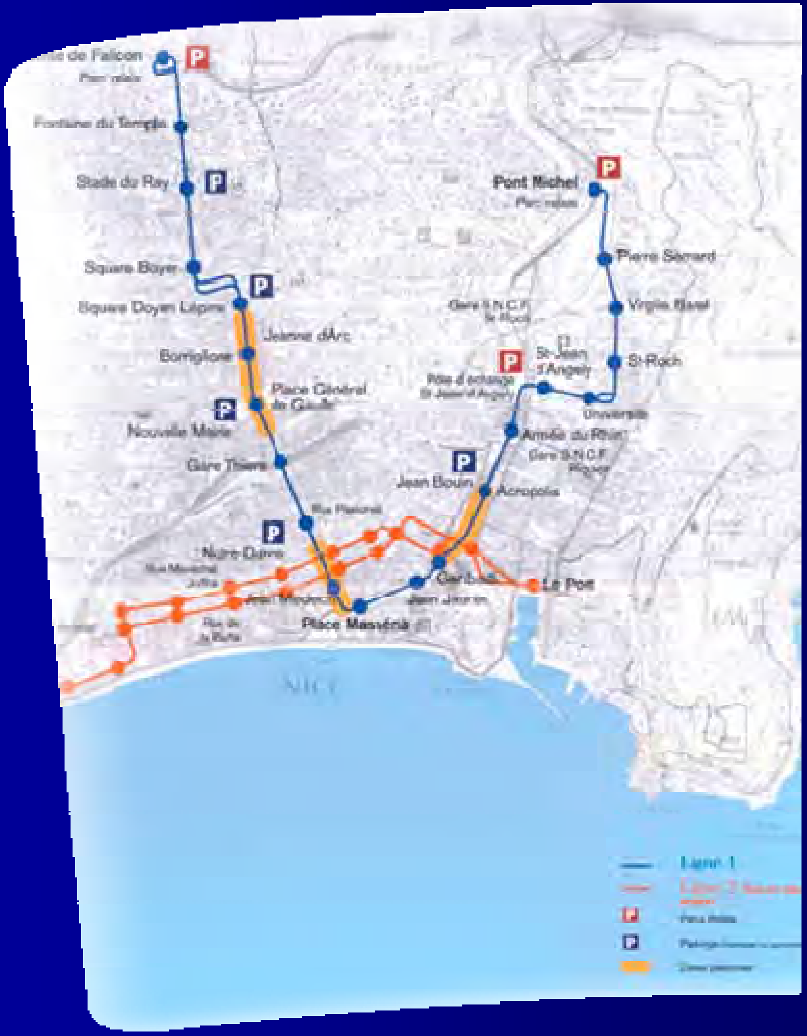
Skoda, Inekon and United Streetcar Trio type streetcars may operate wireless in the maintenance facility or through an intersection in the case of OCS power failure.



*On-board electric energy storage batteries – Nice France

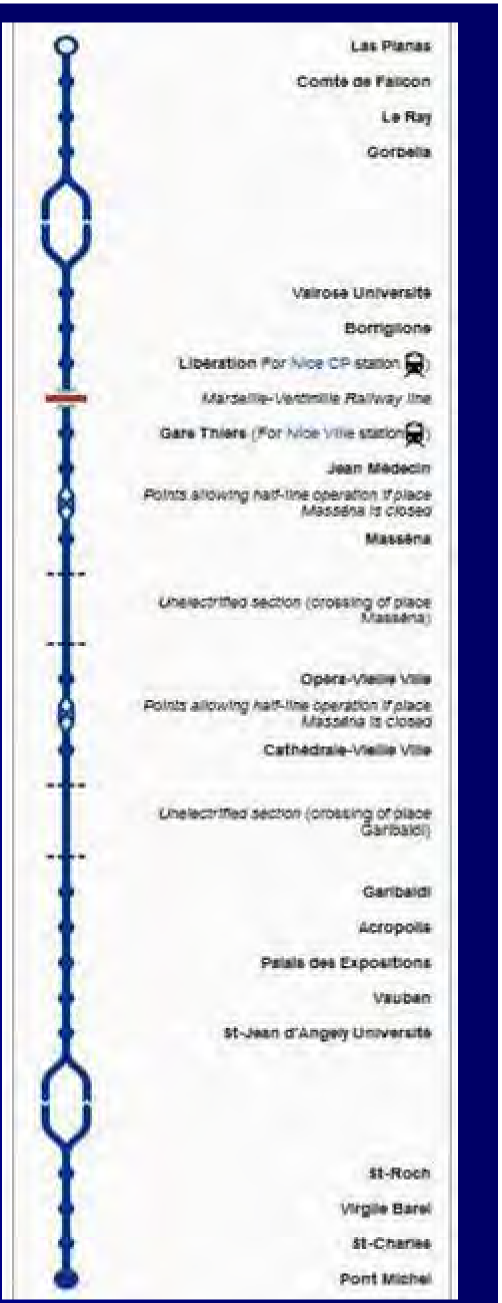
Nice France

- Opened early 2007
- System Length 8.7 km (5.4 mi)
- Alstom Citadis with batteries
- 20 trainsets
- Daily Ridership 70,000



On-board electric energy storage batteries – Nice France

- No OCS on 2 squares , Place Massena (435 m) & Place Garibaldi (485 m).
- Use of roof- fitted NiMH (nickel-metal hydride) batteries capable of providing up to 1km of travel at 30km/h.


Las Planas
Comte de Falicon
Le Ray
Gorbella
Valrose Université
Borriglione
Libération (For Nice CP station)
Marseille-Ventimille Railway line
Gare Thiers (For Nice Ville station)
Jean Médecin
Points allowing half-line operation if place Masséna is closed
Masséna
Unelectrified section (crossing of place Masséna)
Opéra-Vieille Ville
Points allowing half-line operation if place Masséna is closed
Cathédrale-Vieille Ville
Unelectrified section (crossing of place Garibaldi)
Garibaldi
Acropolis
Palais des Expositions
Vauban
St-Jean d'Angely Université
St-Roch
Virgile Barel
St-Charles
Pont Michel

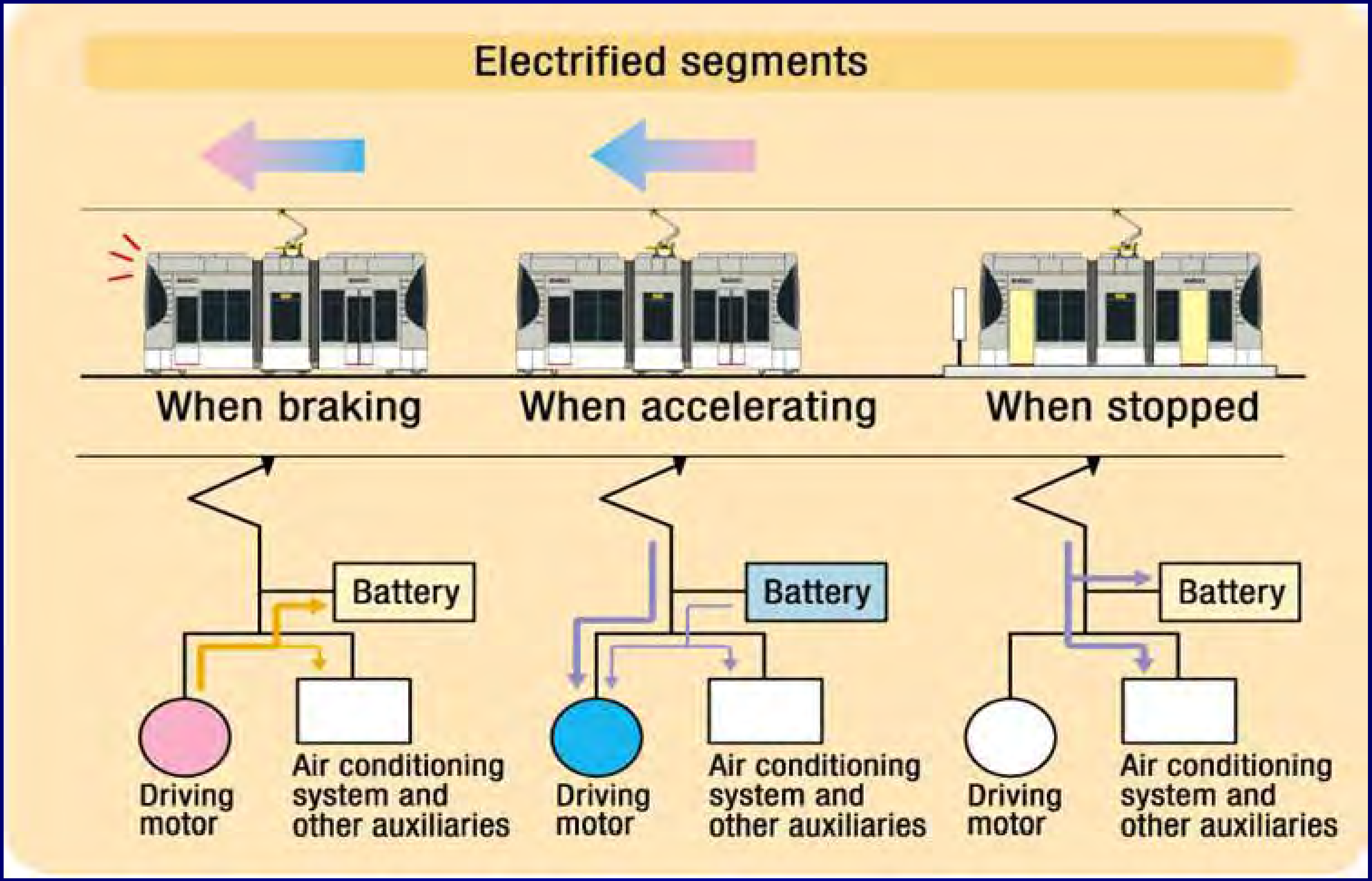
*On-board electric energy storage batteries – SWIMO Battery Tram

Kawasaki SWIMO Battery Car, can operate for 10 kilometers (6 miles) on a single charge of 5 minutes.

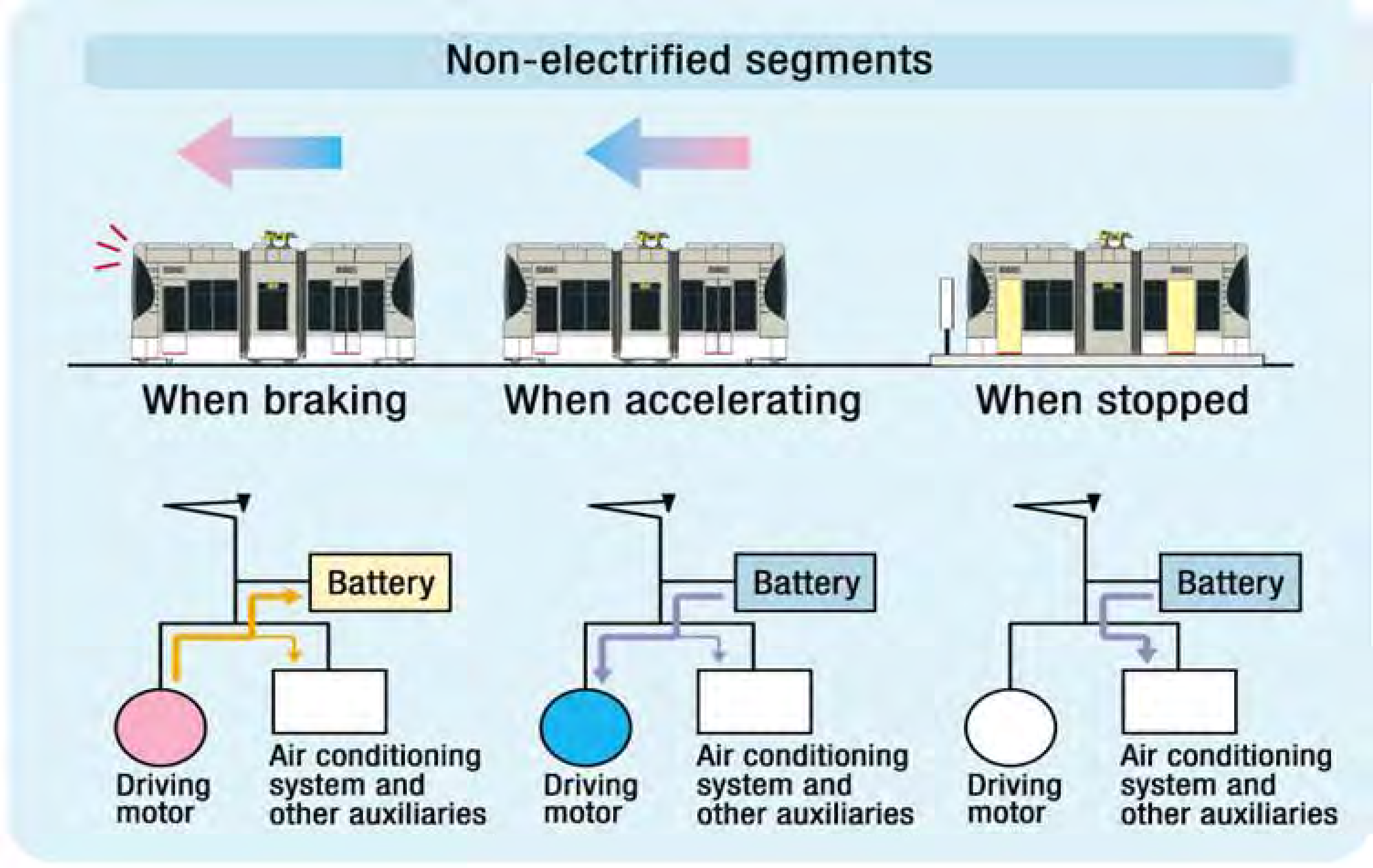
In trials, the best performance was 37.5km without re-charging. Between December 2007 and March 2008, trial runs were undertaken in Sapporo City Japan.

Onboard batteries are nickel-metal hydride.

On-board electric energy storage batteries – SWIMO Battery Tram


Electrified segments
When braking
When accelerating
When stopped
Battery
Driving motor
Air conditioning system and other auxiliaries
Battery
Driving motor
Air conditioning system and other auxiliaries
Battery
Driving motor
Air conditioning system and other auxiliaries

On-board electric energy storage batteries – SWIMO Battery Tram


Non-electrified segments
When braking
When accelerating
When stopped
Battery
Driving motor
Air conditioning system and other auxiliaries
Battery
Driving motor
Air conditioning system and other auxiliaries
Battery
Driving motor
Air conditioning system and other auxiliaries

*On-board electric energy storage flywheel.

In Rotterdam, the Netherlands, Alstom the flywheel. It stores kinetic energy from braking and can be re-loaded on sections with OCS to again deliver energy over an OCS section of up to 2 kilometers at 50 kph.

On-board electric energy storage flywheel.

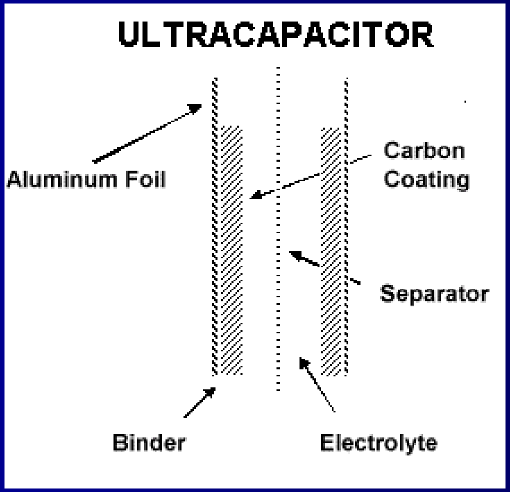
A carbon fibred rotating permanent magnet motor-generator located on the roof of the tram works on the same principle as a spinning top.

The kinetic energy stored during braking is restored by the electric generator is returned to the propulsion system when the tram accelerates.

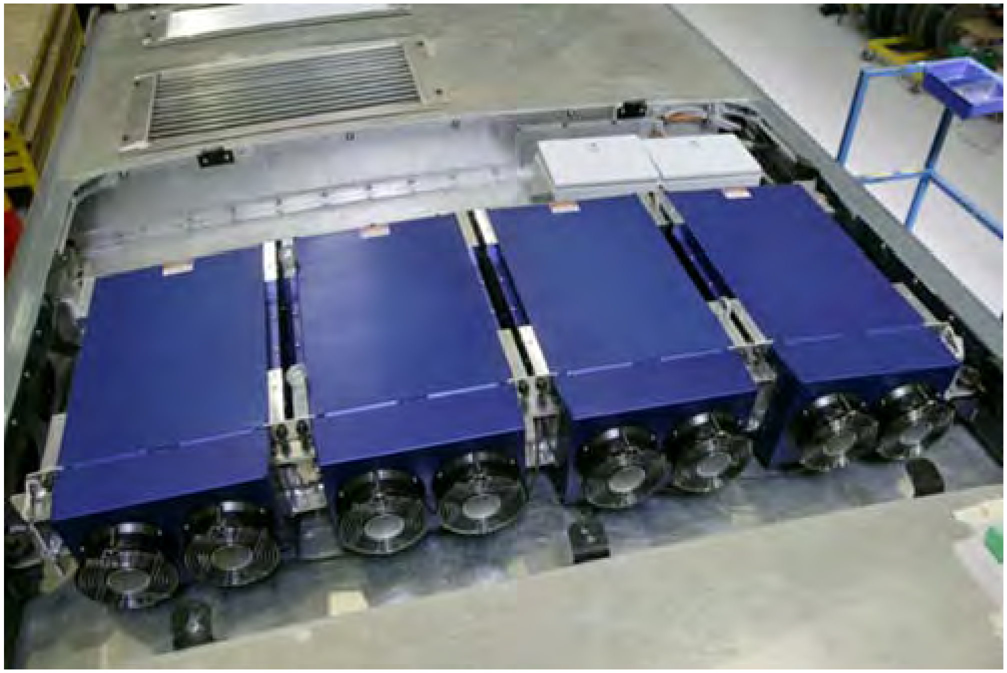
The system is recharged each time the brakes are applied or by a complementary high-speed recharging system each time the tramway stops at a station.

*Power Systems – Storage Capacitors

- Theory behind electrochemical (EC) or double layer capacitors (DLC) known for over 100 years, not until the 1960s was developed as a functional energy storage device.
- Known also as Super or Ultra Capacitors.
- Super capacitors or Ultra capacitors used by the US military to start the engines of tanks and submarines.



On-board electric energy storage super or ultra capacitors.



Banks of Supercaps on the roof of a Scania bus.

*On-board electric energy storage super or ultra capacitors - Mitrac.

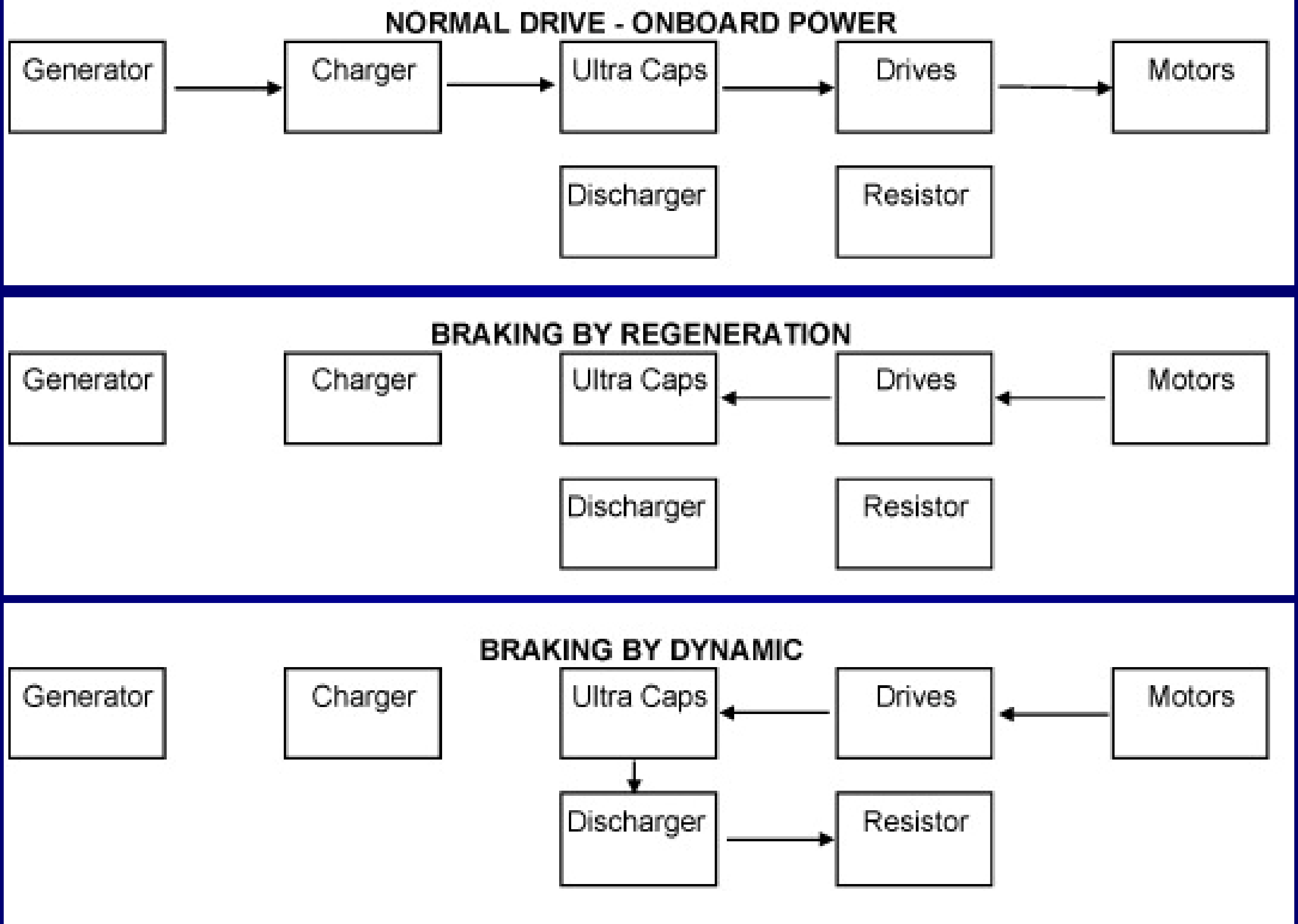
- The PRIMOVE system uses Bombardier MITRAC Energy Saver which ensures continuous vehicle operation.
- Mitrac stores energy during braking and constantly charges during operation, picking up power from the underground section during OCS free operation. Enables OCS free operation over limited distances
- Combination of capacitors and storage cells.

*On-board electric energy storage super or ultra capacitors - Savannah.

- Developed and built by Electric Motor & Supply in Altoona Pennsylvania in 2008 in response to City of Savanna's requirements.
- 100% US.
- May operate with or without OCS.
- Based on Allen-Bradley distributed Rockwell Automation and other off the shelf components with some custom made devices.
- 100% super capacitor powered.
- Operating passenger service since February 2009.

On-board electric energy storage super or ultra capacitors - Savannah.

*On-board electric energy storage super or ultra capacitors - Savannah.



NORMAL DRIVE - ONBOARD POWER

Generator → Charger → Ultra Caps → Drives → Motors

Discharger

Resistor

BRAKING BY REGENERATION

Generator

Charger

Ultra Caps ← Drives ← Motors

Discharger

Resistor

BRAKING BY DYNAMIC

Generator

Charger

Ultra Caps ← Drives ← Motors

Discharger → Resistor

*On-board electric energy storage super or ultra capacitors - ACR.

Construcciones y Auxiliar de Ferrocarriles (CAF) Rapid Charge Accumulator ACR (Spanish initials).

- CAF will install its new OCS free system along a 1.6 km of route of visual significance in Seville (Spain).
- The CAF joint venture has been selected to supply 13 low-floor trams with energy storage for Granada's (Spain) initial 15·9 km light rail route.
- Supply ACR solutions for Zaragoza (Spain) tramway. Zaragoza is currently developing a project for the construction of a tram network, half of which is equipped with an OCS system.

On-board electric energy storage super or ultra capacitors- ACR.

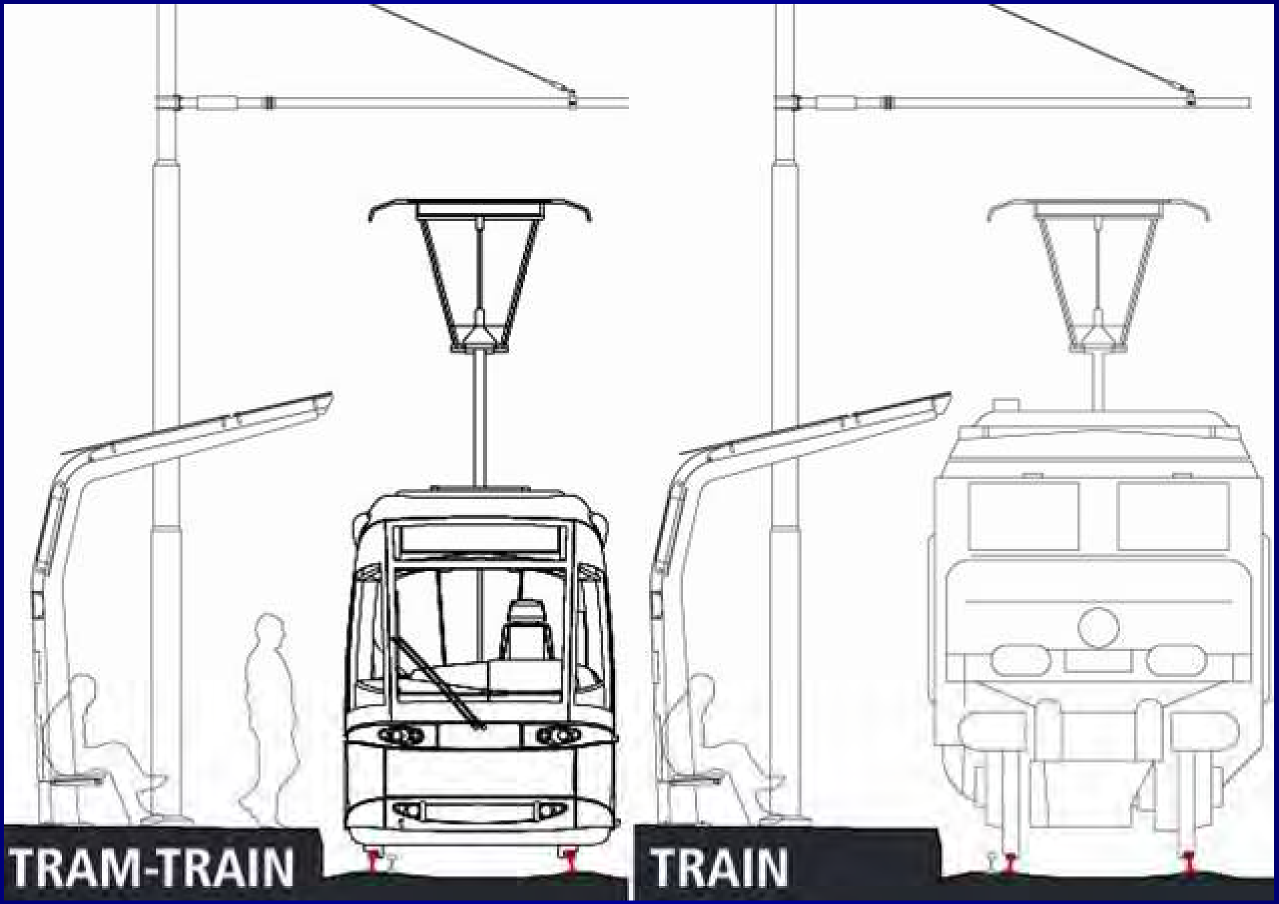
CAF ACR System

- Up to 1200 meters of OCS free running range depending on route characteristics between stops or incidents on the line .
- Modular and scalable .
- Suitable for use on existing systems
- 20 second charge times, compatible with stopping times at stations .
- Non-captive system (material/infrastructure independent) .

*On-board electric energy storage super or ultra capacitors- Sitras.

- Siemans Sitras system can operate without an overhead contact system for 2,500 meters.
- Can can be retrofitted to existing vehicles, infrastructure remains unaffected.
- In Portugal, the system has been successfully used in passenger services since November 2008.
- Certified according to BoStrab (German Construction and Operating Code for Tramways).
- The system consists of double-layer capacitors and nickel-metal hydride batteries mounted on roof surfaces.

*On-board electric energy storage internal combustion engine – Tram/Train.



*On-board electric energy storage internal combustion engine – Tram/Train.

Alstom

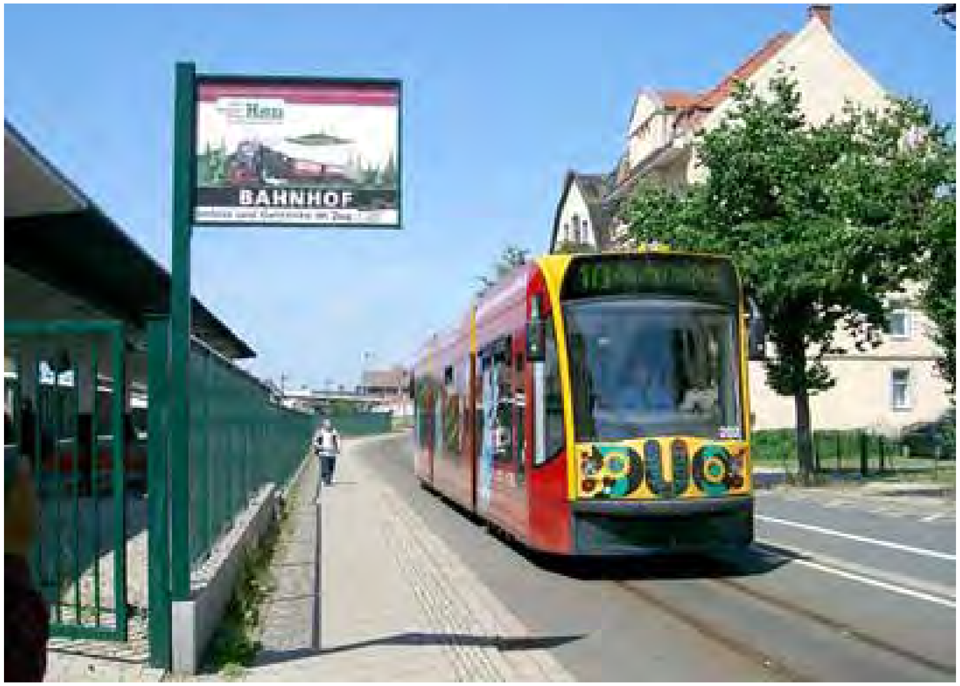
Regio CITADIS (tram) and CITADIS Dualis (Light Rail).

All current railway power supply systems and high performance diesel traction may be incorporated. Full low floor between the first and last doors, Regio CITADIS can carry up to 800 passengers.

*On-board electric energy storage (internal combustion engine, fuel cell).

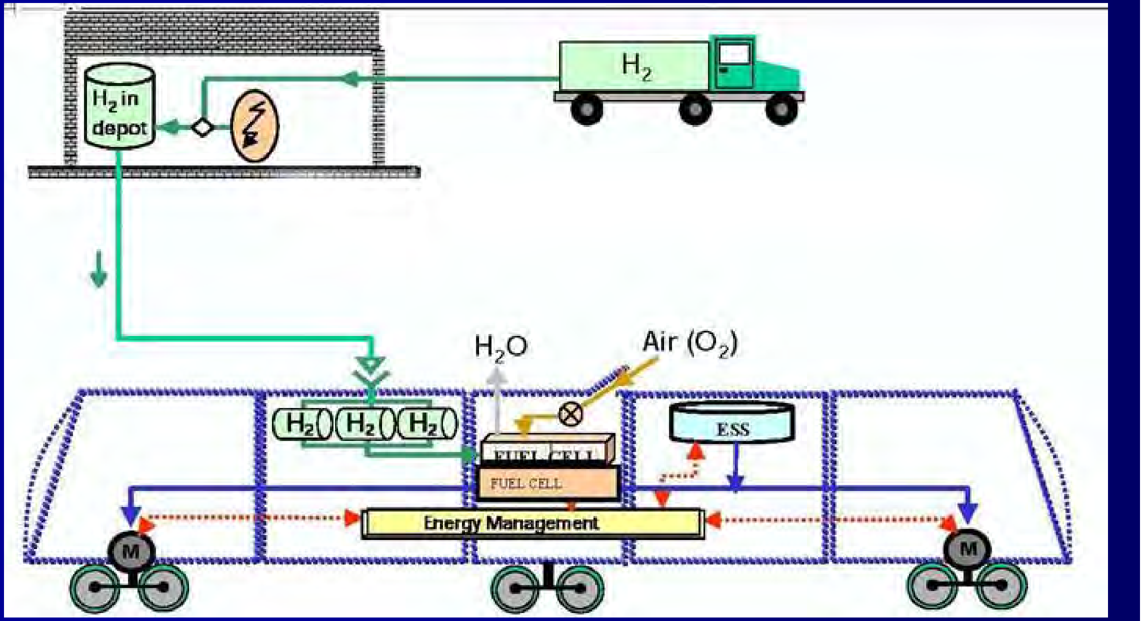
Siemans

A Nordhausen (Germany) Siemans ‘DUO’ Combino linking the urban tramway, where it is electrically powered via overhead wires, and the rural railway, where it is powered by an onboard diesel engine.



*On-board electric energy storage fuel cell.

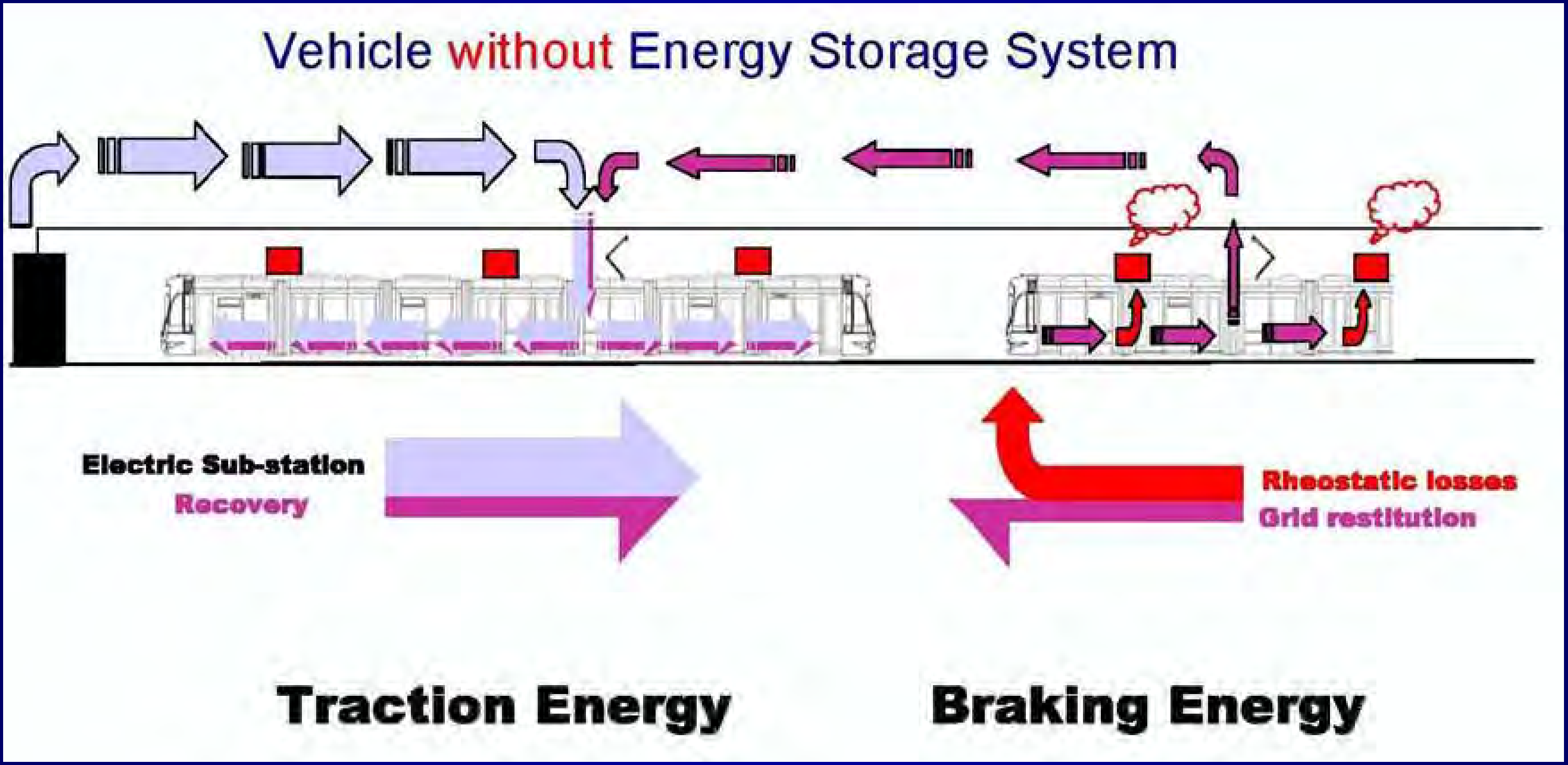
- No overhead Contact Line.
- Hybrid traction system onboard energy storage allows braking energy recovery and supplies power
- Hydrogen storage, compression and distribution in the maintenance facility.
- On-board hydrogen storage.



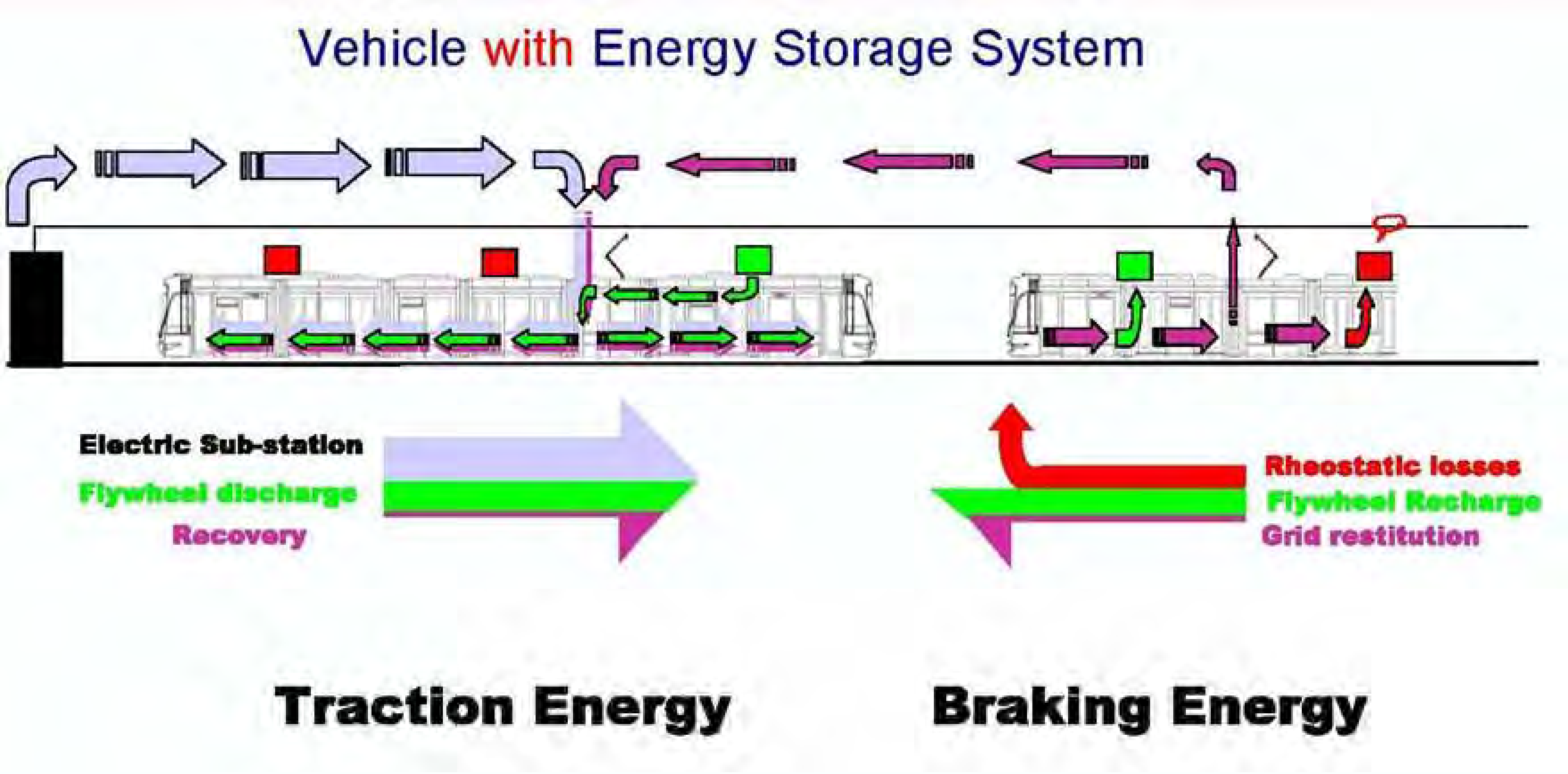
On-board electric energy storage fuel cell.

- State requirements and recommendations for future streetcar generations.
- Experimental streetcar in real operation conditions with passengers.
- Size and type of plant required.
- Production and distribution.
- Assess economical feasibility (Life Cycle Cost)
- Lifetime objective same as actual streetcar systems around 30 years.

*On-board electric energy storage



On-board electric energy storage



Energy Storage Technology

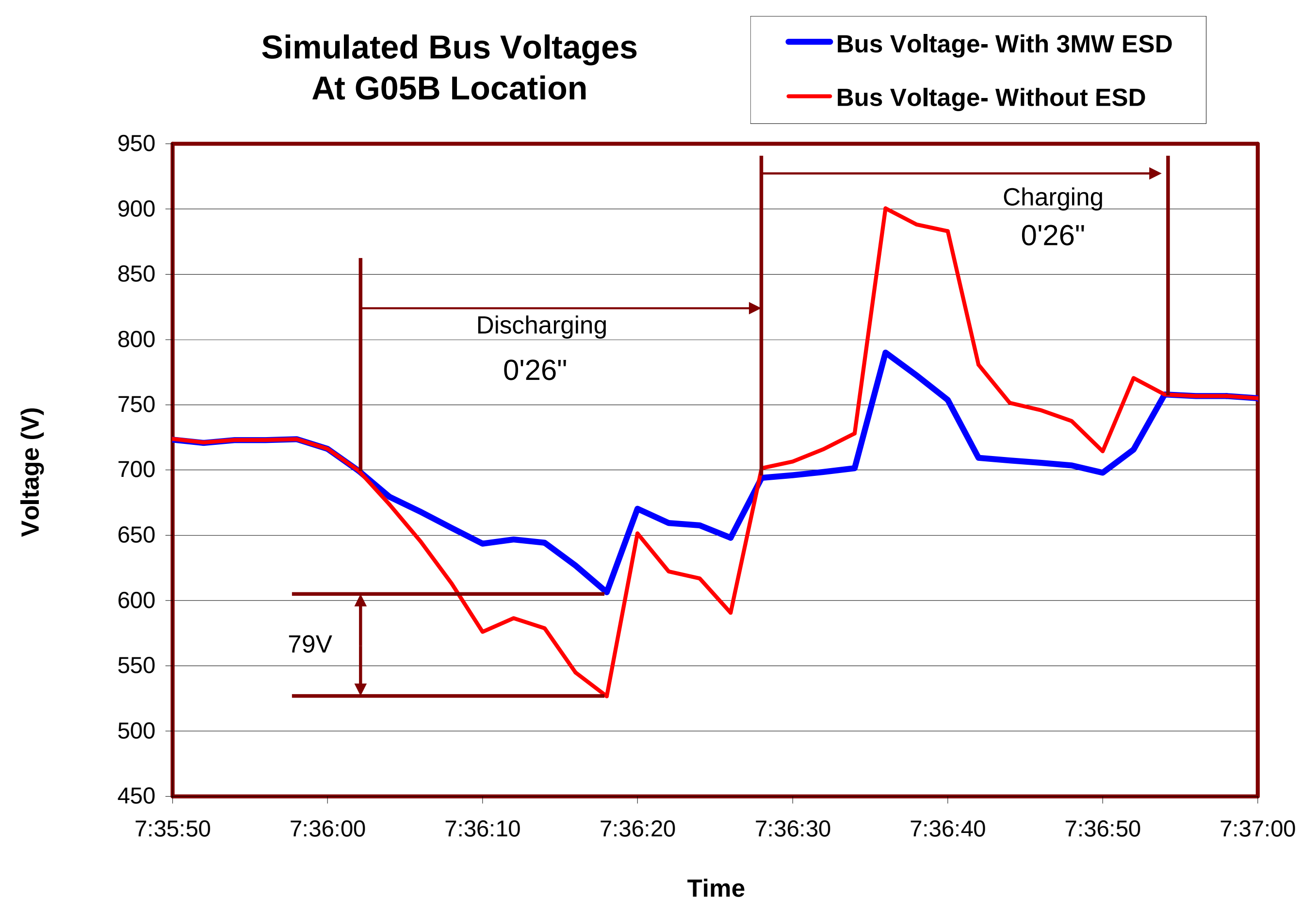
Martin P. Schroeder, P.E.

APTA Streetcar and Heritage Trolley Subcommittee
Chief Engineer, American Public Transportation Association

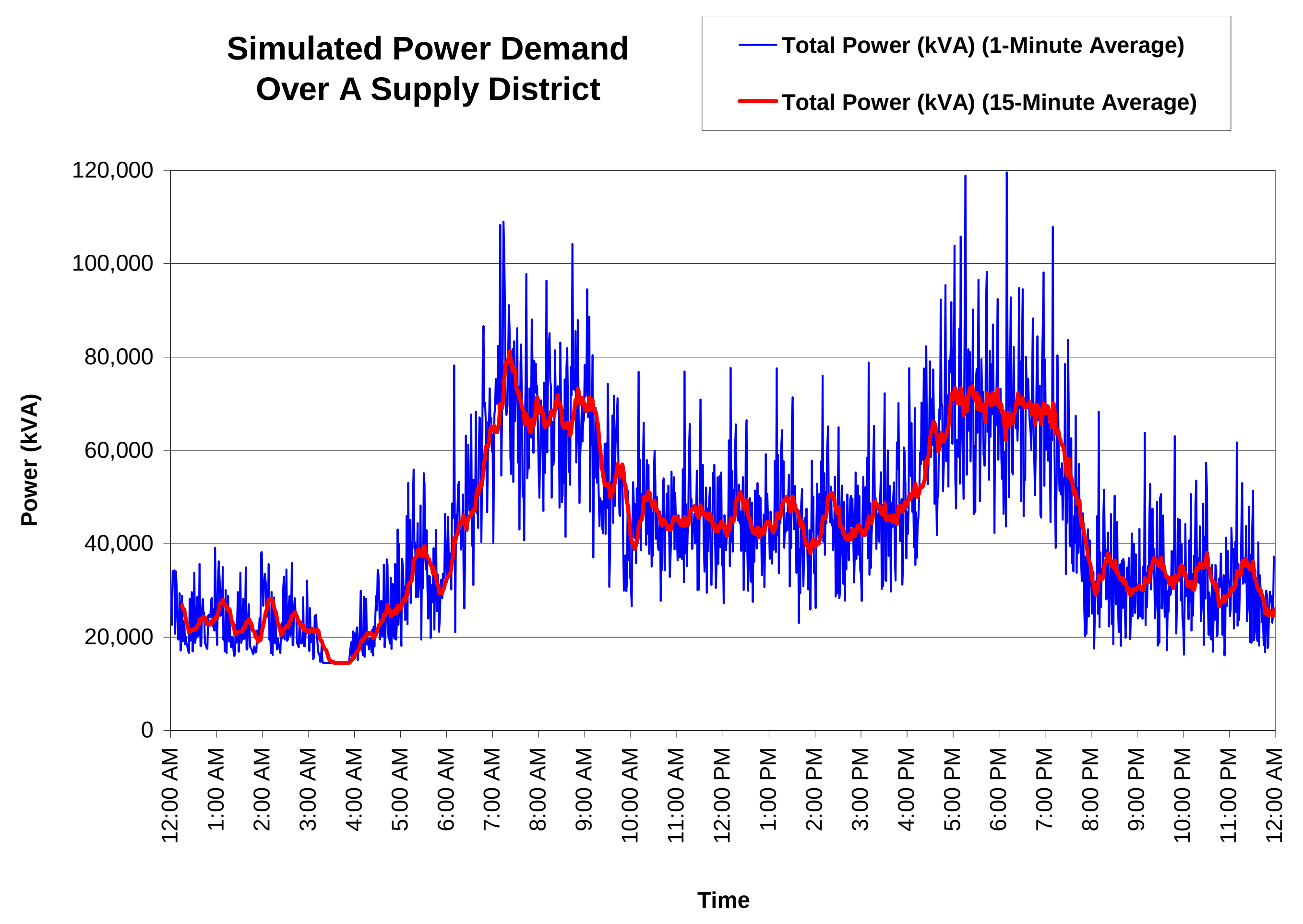
Energy Storage Benefits

- Braking Energy Capture
- Voltage Sag Correction
- Reduction of Line Energy Demand
- Power Leveling
- Reduction of Substations
- Wireless Operation

Voltage Sag Problems



Peak Power Problems



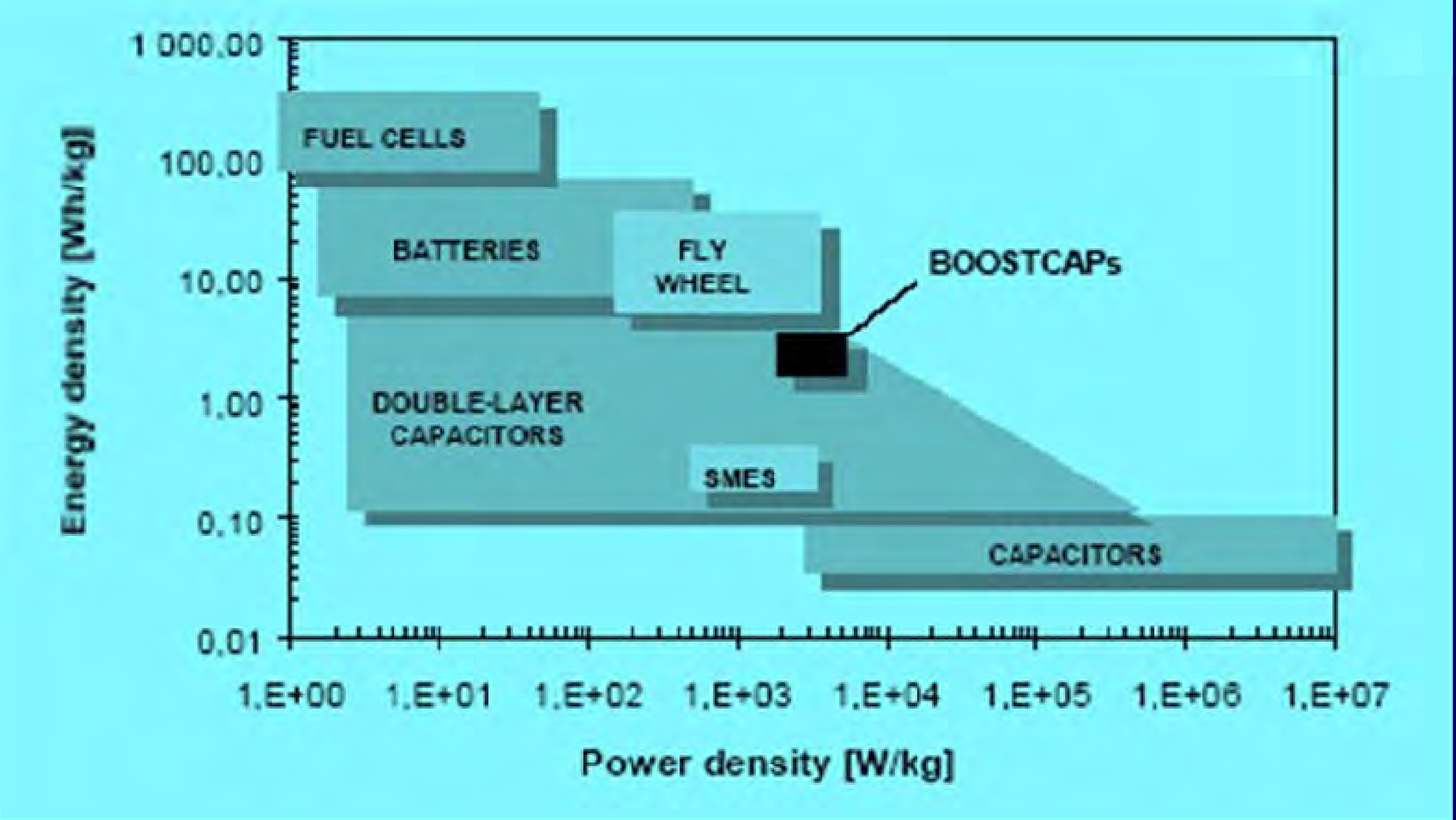
Example Types of Energy Storage

- Lead Acid
- Nickel Metal Hydride (NiMH)
- Lithium Ion (Li-ion)
- EC Capacitor
- Fuel Cells
- Flywheel
- Flow Batteries
- REDOX

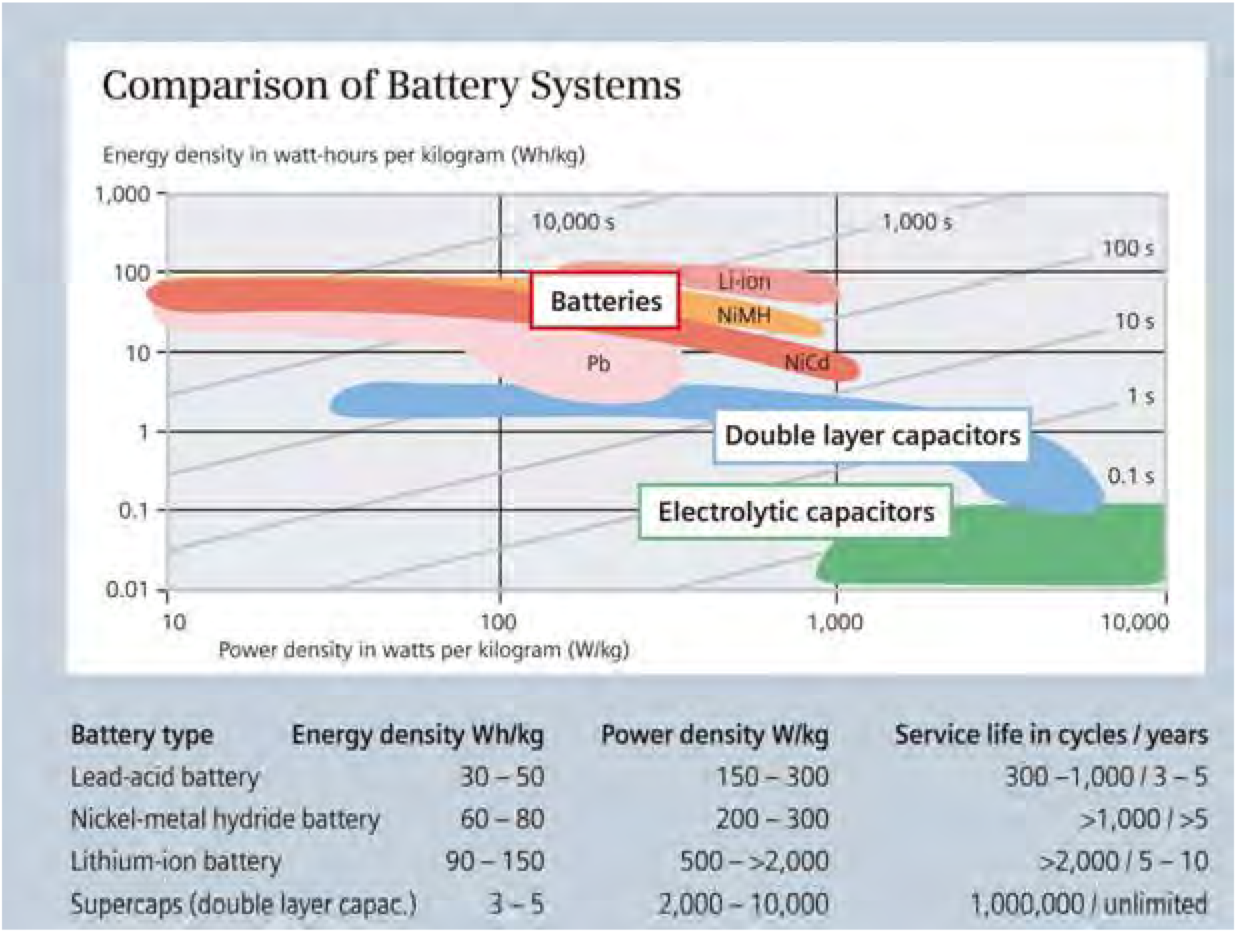
Energy Storage Performance Measures

- Capacity
- Cycle Depth
- Cycle Frequency
- Voltage
- Internal Resistance Efficiency
- Operating Temperature
- Shelf Life
- Discharge and Charge Rates

Ragone Diagram



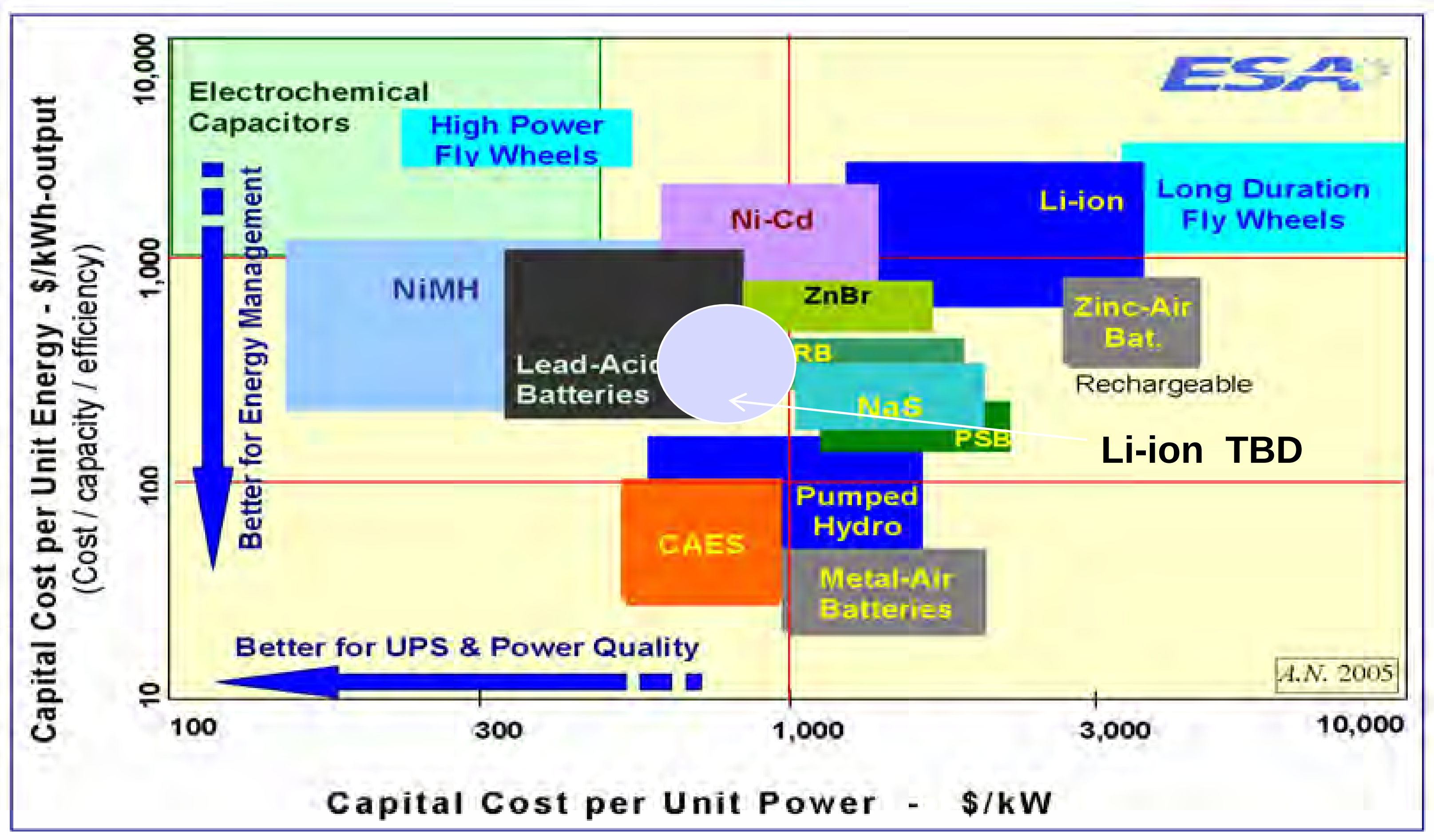
On-board electric energy storage (batteries, flywheels, super capacitors)



Comparison of Battery Systems

Battery type	Energy density Wh/kg	Power density W/kg	Service life in cycles / years
Lead-acid battery	30 – 50	150 – 300	300 –1,000 / 3 – 5
Nickel-metal hydride battery	60 – 80	200 – 300	>1,000 / >5
Lithium-ion battery	90 – 150	500 – >2,000	>2,000 / 5 – 10
Supercaps (double layer capac.)	3 – 5	2,000 – 10,000	1,000,000 / unlimited

Energy Storage Cost Points



Li-ion TBD

Energy Density

Nuclear	645,000,000
Automotive	8.10
Fuel Cell	1.62
Zinc Air Battery	1.33
Sodium Sulfur	0.77
Lithium Ion	0.54
Flywheel	0.5
NiMH	0.22
NiCd	0.14
Lead Acid	0.09
Redux	0.09
EC Capacitor	0.02
Spring	0.0003

For relative comparison only.

Advances in technology are changing capacities of these devices.

Possible Energy Storage Configurations

- Alignment
  - No Gap
  - Limited Gap
  - Full Storage
- Utilization of Regenerative Braking
- Power Quality & Voltage Sag Protection
- Efficiency

Putting it Together - Needs

- Alignment Definition
  - Terrain
  - Stops
  - Lengths between stations
  - Lengths of wireless operation
  - Ridership
- Vehicle Design
  - Storage
  - Regeneration
  - Efficiency
  - Maintenance

On-board Energy Storage Devices Receiving Significant Attention

- NiMH
- EC Capacitor
- Li-ion
- Hybrid – Battery / Capacitor
- Fuel Cell
- Flywheel

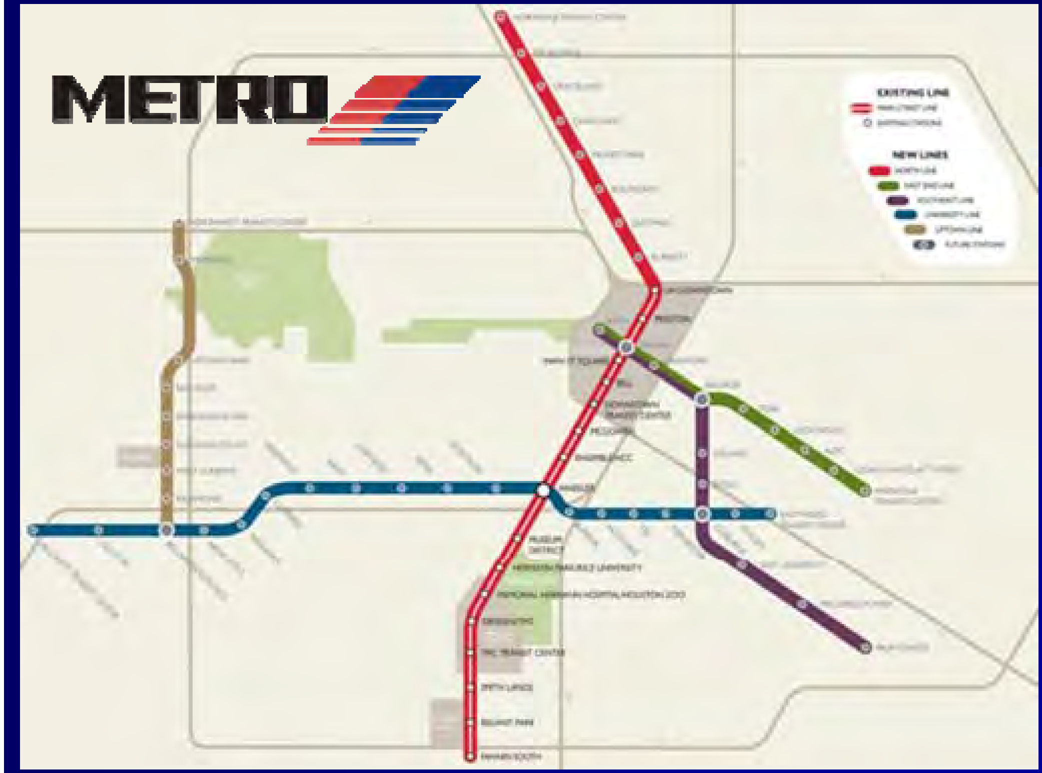
Practical Considerations

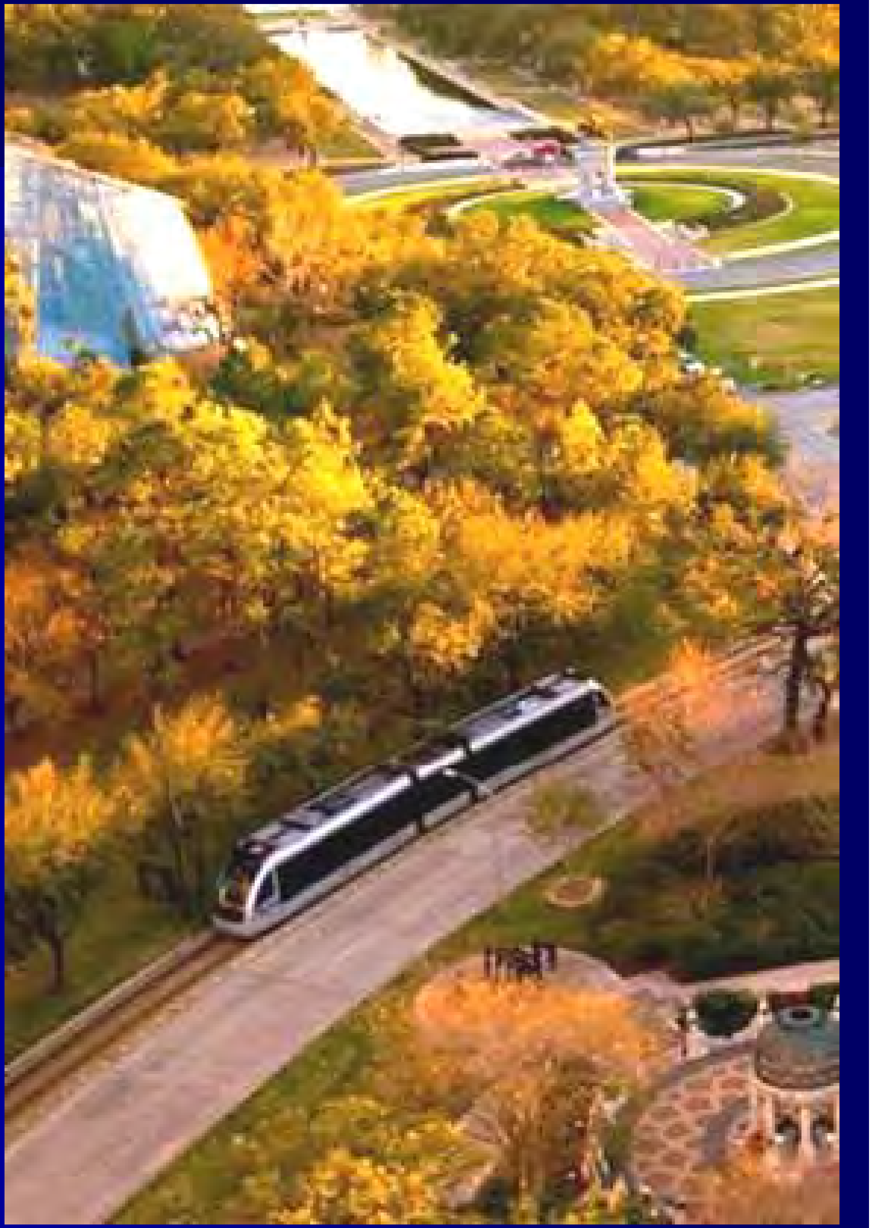
- Operations
- Maintenance
- Risk – Cost, Service, Experience, etc.
- Cost Investment / Payback
- Reliability
- Fit to Function

Implemention and Operations

T. R. Hickey, AICP

Vice Chair, APTA Streetcar and Heritage Trolley Subcommittee
Associate Vice President
Metropolitan Transit Authority of Harris County
Houston, Texas


METRO
EXISTING LINE
NEW LINES



SEPTA

Operator's Checklist

- Safe?
- Reliable?
- Affordable?
- Sustainable?

Are the RISKS manageable?

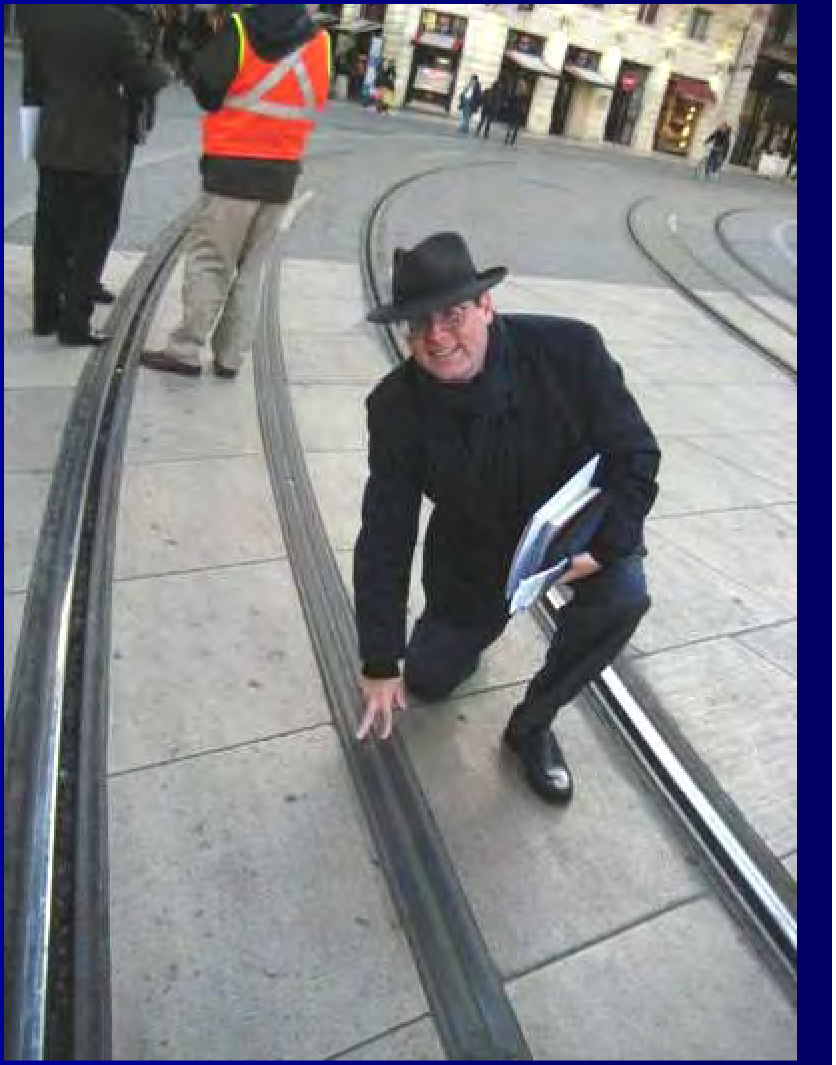
A Tale of Two Agencies...

Risk Management

- Begins with a Risk Management Plan
  - – FTA Risk Assessment Process
    - Design/construction risks
      - – What events may occur to the detriment of the project?
    - Probability
      - – How likely is it that each event will occur?
    - Financial risk
      - – What would it cost to mitigate/recover from an occurrence?
  - – Defined and managed through a Risk Register

Risk Management

- Risk Management vs. Risk Avoidance
  - – Assess your risks
  - – Don’t shy away from emergent technologies
    - But maintain realistic skepticism
    - Have a ‘B’ Plan ready



Practical Experience

James H. Graebner

Chair, APTA Streetcar and Heritage Trolley Subcommittee
President, Lomarado Group
Denver, Colorado

Summary

	Visual Impact	Capital Cost	O&M Cost	Proprietary Technology	Proven Reliability
POWER SUPPLY SYSTEMS					
Overhead Contact System	🟡	🟢	🟢	🟢	🟢
Underground Conduit System	🟢	🔴	🔴	🟢	🟢
Ground-Level Systems					
Contact	🟢	🔴	🔴	🔴	🟡
Contactless	🟢	🔴	?	🔴	?
On-Board Generation					
Internal Combustion	🟡	🟡	🟡	🟢	🟢
Fuel Cells	🟢	?	?	?	?
POWER STORAGE SYSTEMS					
Batteries	🟢	🟡	🟡	🟢	🟢
Capacitors	🟢	🟡	🟡	🟢	🟡
Flywheels	🟢	?	?	🟡	?

🟢 No Issues
🟡 Minor Issues
🔴 Major Issues
? Unresolved

Thank you

RAIL INFRASTRUCTURE
DELIVERING LIFECYCLE SOLUTIONS

ALSTOM

Catenary installation on high speed line, Reggio Emilia - Bologna, Italy

Track work on the Lausanne metro, Switzerland

TRACK FOR ALL TERRAINS AND TRAINS

Alstom offers a complete portfolio of rail transport infrastructure services, with the expertise and plants and tools to assure the success of any project. We design and supply new systems, upgrade existing ones and provide maintenance for any length of time: Track work, catenaries, power supply, control systems, station utilities and depot workshops.

THE DECISION OF A LIFECYCLE

The search

Urban transit authorities, mainline rail infrastructure managers and rail freight operators work in very different contexts, but they share the same basic concerns in infrastructure: they need completely safe lines they can rely on to optimise their overall performance and lifecycle costs, while satisfying their customers. In new infrastructure and renovation projects, decision-makers weigh engineering solutions, seeking the best value for money at lowest risk. Which company is most likely to deliver on time, to cost and to contractual commitments? Who understands local conditions best and has the flexibility to assure the least disruptions?

Proof of capability

Alstom provides expertise in rail infrastructure through every step including design, engineering, procurement, construction, commissioning and maintenance. Drawing on a 30-year track-record in over 25 countries, Alstom alone has the experience in project management and advanced technology to offer a complete range of lifecycle solutions for track, electrification and electromechanical equipment along the line, in stations and in depot. Not every customer requires such a wide scope of state-of-the-art services, but every project we undertake profits from our resources and expertise. Whether integrating a high speed rail system or just adding track ballast, we deliver the same degree of professionalism. We engineer for functionality and performance. Our specialists draw on our detailed understanding of the entire rail system, to solve interface issues.

Athens Suburban Substation

INFRASTRUCTURE SOLUTIONS FOR EVERY RAIL NEED

For every type of rail infrastructure project, we offer expert design and engineering services for new solutions and optimised lifecycle costs. We provide the plant and tools needed on site, the skilled labor and project management. We provide project management for integration and commissioning on a full turnkey basis or separately. We also provide renovation and maintenance services.

TRACK

Alstom has strong worldwide experience in providing rail infrastructure solutions for tramways, metros, high speed lines and main lines with ballast or concrete. Our major references in track systems total more than 2000 km of single track already built or under construction around the world. Our primary added value is in providing project management expertise and construction with full deployment of resources, including a large department of specialists in conceptual engineering, global performance and detailed design. For new tram lines, we can provide our own Appitrack technology, fully validated for all LRT projects. Appitrack enables us to accelerate track work and minimise worksites to reduce disruption to city life.

ELECTRIFICATION

We provide full electrification services for new and existing urban and main lines: catenary and power supply design and engineering, procurement, installation, commissioning and maintenance. We have installed 10,000 km of catenary worldwide and contributed to hundreds of power supply projects. Our APS street-level power supply for tramways eliminates overhead wires, preserving the city's character.

- Technical expertise: we can deliver a catenary suitable for any current (AC/DC), from 750 V to 2x25 Kv 50 or 60 Hertz and for all types of speeds, from 70 to 350 km/h.
- Innovative solutions: for energy savings and environmental respect. EMI/EMC management reduces electromagnetic interferences.

ELECTROMECHANICAL WORKS

We offer a full range of E&M solutions for stations and tunnels. Transport authorities rely on us for the design, supply, integration and commissioning of systems for road & tramway signalling, telecommunications and passenger information, platform screen doors, as well as equipment for security, ventilation, automatic fare collection (ticketing), and depots.

MAINTENANCE

Alstom maintains rail infrastructure equipment and systems worldwide under short or long-term contracts with performance and availability guarantees. Maintenance, parts logistics and renovation services represent over 20% of our business. Our experts design each maintenance programme using state-of-the-art methodology, processes and organisations to answer needs at a local level. Full or specific maintenance includes rapid-response, corrective and preventive care, main revisions or overhauls, damage repair.

Six reasons to consult Alstom on rail infrastructure

1.Expertise in rail infrastructure design and engineering

2.Proven, innovative technology to suit each project

3.World-class project management expertise and experience for smooth interfaces and on-time delivery

4.Local teams recruited and trained for lasting added value

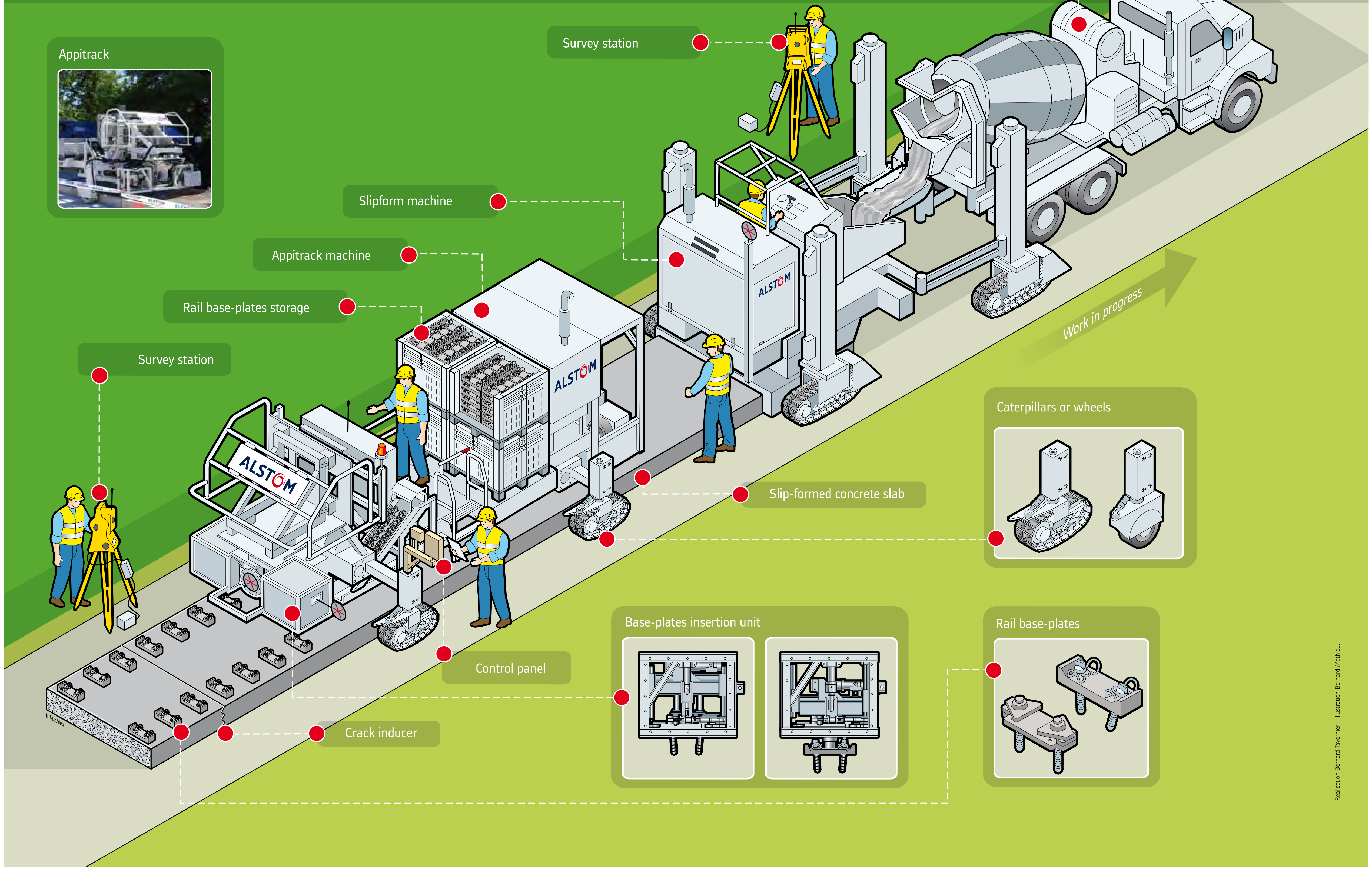
5.Guaranteed quality at competitive prices

6.Commitment to customers through life-time support

Catenary maintenance, Barcelona LRT

APPITRACK

Automatic Pin and Plate Insertion for Track



Réalisation Bernard Tavernier - Illustration Bernard Mathieu.

Appitrack: our way to lay track

Faster, better, quieter

Appitrack is an innovative process developed by Alstom for laying tracks on concrete, similar to the method used for building motorways or runways. It can be used for all light rail projects with all types of surfacing. The process involves two machines: a slipform machine, which constructs the trackslab, and behind it an insertion machine, which automatically positions and inserts railseats, holding down bolts in fresh concrete. It is guided by an on-board pc and communicates with a survey station post for high precision rail positioning. By 2010, Alstom will have laid over 100 km of track using our Appitrack system, in Algiers, Jerusalem, Reims and Orleans.

Key benefits

- Preserves the environment
- Reduces civil work
- Accelerates construction
- Minimises disturbances to neighborhood
- Uses the latest proven technologies
- Ensures cost effective, high quality track construction

APS Aesthetic Power Supply

Open skies for cities

A modern, clean, quiet technology for transport in city centres, APS (for *Alimentation par le sol*, or ground-level power supply) is a proven power system developed by Alstom for light rail. By supplying electricity at ground level, APS makes it possible to do without overhead wires. With APS, cities can introduce tram service to their historic quarters while respecting their unique characters.

Bordeaux leads the way

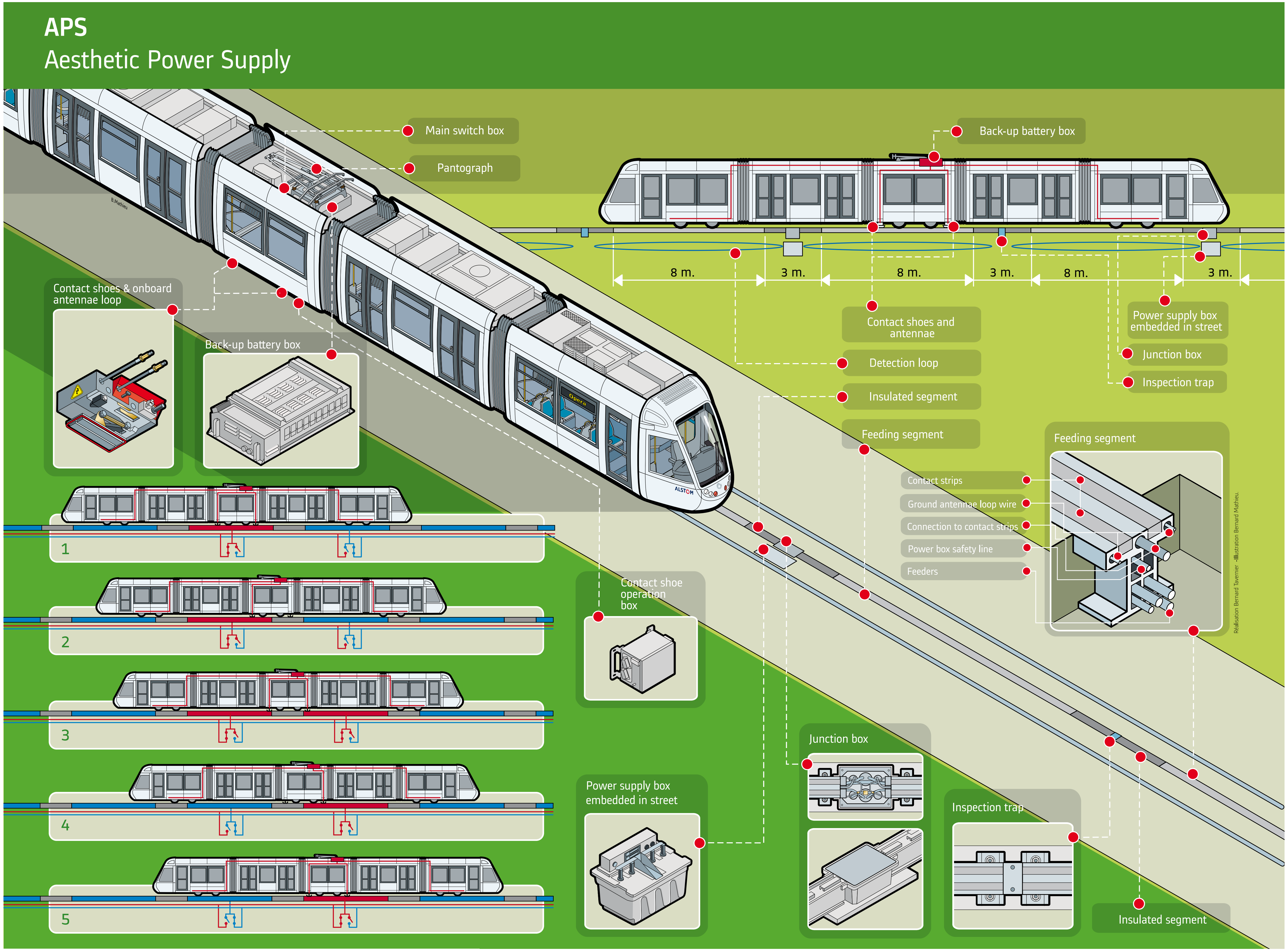
Bordeaux, one of France's most visited cities, was the first city to recognise the APS advantage. The open-sky system, integrated over 13 km of its 44 km tramway network, has a 99.8% rate of availability. The French cities of Reims, Angers and Orleans ordered APS systems in 2006. More than 15 km of APS will soon be installed and operated in Dubai, on the Al Safooh line.

Award-winning technology

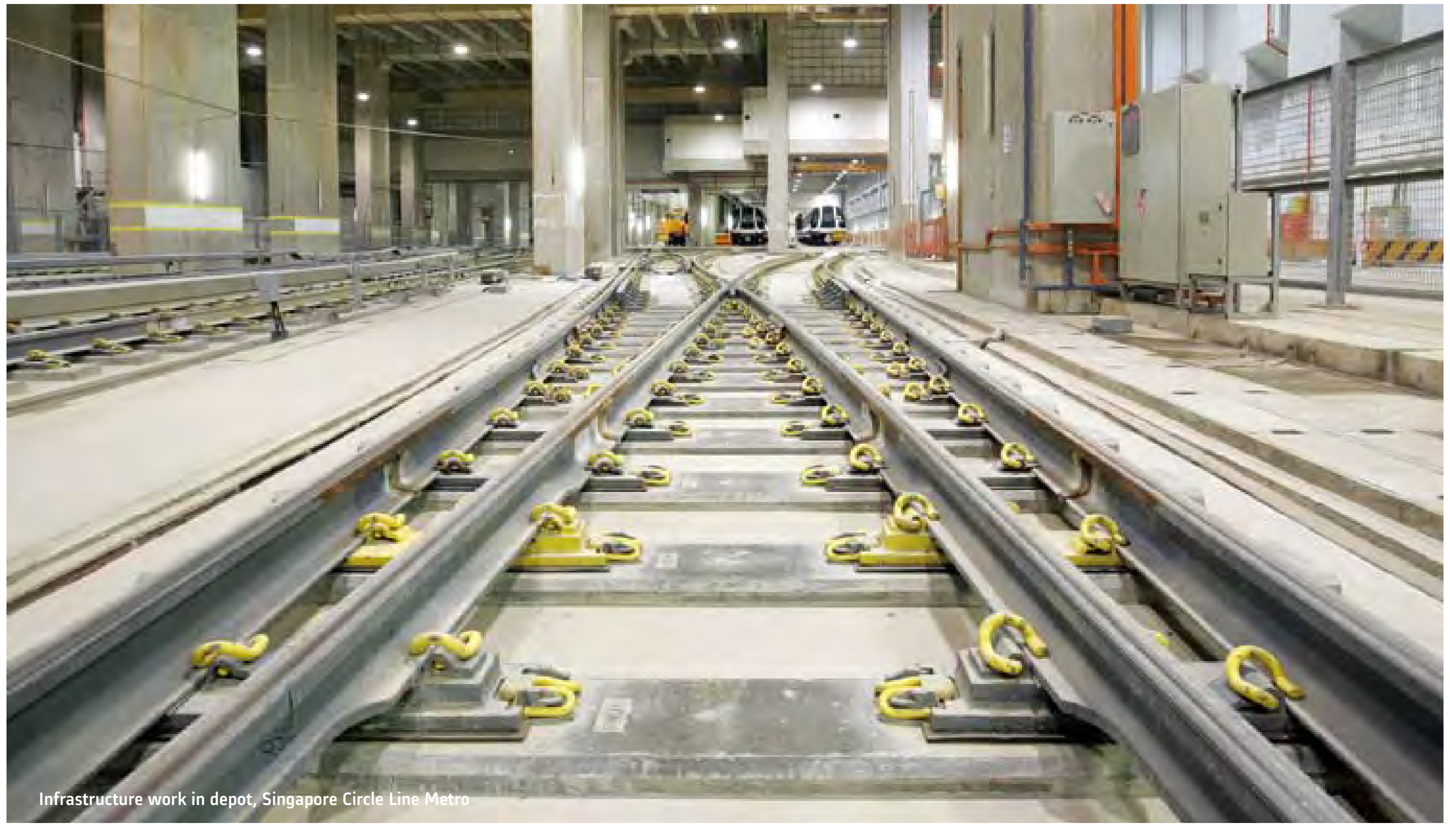
APS functions via a third rail embedded in the ground. Conducting segments are placed at regular intervals, separated by insulated joints. The segments are supplied by power boxes, only activated when the tram passes directly over them to ensure perfect safety for pedestrians and traffic. The power supply is triggered by coded radio dialogue between tram and ground. Power is collected through two collector shoes located in the tram's mid-section.

Key benefits

- Preservation of historic sites and urban environment
- High reliability for optimum tram performance
- Fully modular system
- Total safety for pedestrians and car traffic
- Elimination of overhead obstacle to firefighters' ladders



OUR INFRASTRUCTURE REFERENCES


Infrastructure work in depot, Singapore Circle Line Metro

Alstom-supplied LRT system in Lyons, France

TRAM TRACK
LYONS, FRANCE

For the design, supply and installation of the third tram line T3 in the city of Lyons, transit authorities Sytral chose Alstom. Alstom had previously supplied 52 km of single track and the depot for lines 1 & 2 between 1998 and 2003. The new 14.6 km tram line, the first ever to use ballast track, was delivered in 2006.

METRO TRACK
SINGAPORE CIRCLE LINE

When it opens in 2010, Singapore's new 33-km Circle Line will be the world's longest fully automatic metro. Land Transport Authority selected an Alstom-led consortium to design and supply the line's core system in 2000, following the success of its North East line, delivered by Alstom in 2003. Today, the NEL transports up to 2000 passengers per train with headways as low as 90 seconds. For the 31-station Circle Line, Alstom's scope of activity includes the track work (41 km of double track in tunnel and depot, 140 turnouts), power supply with 3rd rail, rolling stock, signalling, and the overall system integration.

Catenary installation and works on High Speed 1, UK

ELECTRIFICATION AND E&M FOR URBAN TRANSIT
SAO PAOLO METRO LINE 4

Only 66 months, including the tunnel boring and other Civil Works activities, to deliver the first three stations of the new line 4, 72 for the rest—these are the customer requirements for this infrastructure project, underway since March 2004. Alstom is responsible for the design, manufacture, installation and commissioning of the line's E&M systems. This covers rigid catenary , high voltage power supply substation, traction substations with thyristor rectifiers, low and medium voltage power supply networks, auxiliaries, elevators/escalators and telecom systems.

ELECTRIFICATION FOR MAINLINES
HIGH SPEED 1 (CTRL 2), UK

Delivered in 2006, High Speed 1 (formerly CTRL 2) links the Channel Tunnel to the new London terminus, St. Pancras. The 40 km section of high speed line can handle eight Eurostar trains per hour at 300 km/h. In the tunnel, noise from passing trains is reduced and vibration attenuated by 32 db thanks to an innovative track bed on concrete base, designed and installed by Alstom. Our scope of work included the design, procurement, and installation of CTRL 2 track and overhead line equipment. Our project management experts also delivered and coordinated the overall logistics for all electromechanical contractors, designed, built and operated two construction rail heads, and performed the testing and commissioning of the entire railway system—20 km of open double track and 20 km of double track under London and the Thames.

And also...

Tramways:

Norway Bergen electrification

Italy Firenze electrification and track

France Bordeaux, Grenoble & Toulouse track

Montpellier & Strasbourg electrification

Algeria Algiers turnkey infrastructure

Tunisia Tunis electrification

Metros:

France RATP Signaling works

Brazil Brasilia maintenance

Taiwan Taipei track

Switzerland Lausanne electrification and track

Chile Santiago L5 electrification and track

Venezuela Caracas Los Teques electrification

Main Lines:

Italy Very High Speed Lines electrification

Spain Very High Speed Lines electrification

Korea KTX Very High Speed Line electrification

China Shi-Tai High Speed Line electrification

France RFF TGV Est signaling works

France SCNF catenary works

Morocco Meknes-Fes main line track

Turkey Marmaray Crossing turnkey infrastructure

Greece Athens Suburban electrification

LRT system, Barcelona, Spain: Alstom has a 25-year maintenance contract for infrastrucuture and rolling stock.

Night maintenance on the Dublin LRT, Ireland

E&M FOR URBAN TRANSIT BARCELONA TRAMWAY

Trambaix and Trambesos, Barcelona's two tram lines, are BOT concessions. The contract for the network, a total of 30 km. and 58 stations, was awarded by city transport authority ATM to an Alstom-led consortium in 2000. Alstom's scope of activity included power substations and on-line cabling, design and construction of the maintenance depots, telecom, signalling and ticketing systems. All were delivered on time in 2004.

MAINTENANCE FOR URBAN TRANSIT DUBLIN TRAMWAY NETWORK

Maintenance takes on its broadest scope with Dublin's LRT: our staff provides total care for the Red and Green lines—50 km with 36 stops, two depots and a fleet of 40 cars. Service covers cleaning, inspection, rapid-response and preventive and corrective maintenance for tracks, overhead catenaries, power supply, signalling, automatic vehicle location system, telecoms and landscaping. The 5-year contract, awarded to Alstom in 2004, is based on availability and quality performance obligation, and includes maintenance plans and management system covering full operations: sales, finance, material and service.

INFRASTRUCTURE AND THE FULL ALSTOM OFFER

Alstom has the expertise and experience to offer a complete lifecycle infrastructure solution, from design through installation, testing, commissioning and maintenance.

THE UNDERSTANDING

Unlike other aspects of the rail industry, infrastructure only exists in situ – and no two sites are alike. Each infrastructure project has its own environment and requirements, based on geography, interfaces with third parties, technology, current use and growth, safety, operator and passenger expectations.

THE EXPERIENCE

As the product is the site itself, success is never a foregone conclusion. Our project managers are able to assure smooth interfaces whatever the volume or complexity in main line or urban projects because they have the experience to draw on. Alstom is the market leader in turnkey urban and mainline rail transport systems, with references worldwide.

PROJECT MANAGEMENT

Infrastructure projects are largely about coordination. They call for excellent project management—a team with the PM tools and processes, expertise and experience to be able to assess the job correctly and plan the most efficient solutions, anticipating all eventualities to guarantee on-time delivery of a high-quality system. Our role is to optimize and integrate schedules, manage costs and deliver quality.

Our Citadis tramway on Bordeaux's "Pont de Pierre" is powered by APS technology.

COMPLEMENTARY ACTIVITIES

- Signalling

Alstom designs, manufactures and installs rail control signalling systems and information technology solutions: CBTC manned and driverless metro traffic control, ERTMS-ETCS mainline rail traffic control systems for interoperability, and a wide range of E&M products.

- Trains

Alstom designs, builds and commissions a full range of rolling stock for urban and mainline use.

- Maintenance

Alstom provides lifecycle maintenance services for trains and signalling systems, as well as infrastructure, with contractual guarantees for availability, spare parts and integrated logistics.

INTEGRATION

Since we cover every aspect in rail, we can optimise all elements in the system: they are literally made to work together. With decades of experience, we can equally integrate other companies' products to work just as well. Our level of expertise allows a dialogue between experts.

THE RESOURCES

Our commitment to the transfer of our skills and expertise adds lasting value to the region. Our local team makes us easily available, able to carry out a technical dialogue locally for greater reactivity.

CONTINUOUS INNOVATION

We're not resting on our laurels. In track and catenary, we listen to our customers and innovate as necessary with significant R&D resources. APS and Appitrack are two of Alstom's innovative rail transport technologies. In addition Alstom is a member of the European Research Program for Urban Track and Innotrack.

Through its know-how and the excellence of its products, Alstom is shaping the future of energy and transport infrastructure and contributing to improving the living and working conditions of people throughout the world. Today, more than 65,000 people in 70 countries are making an active contribution to the growth and development of its business.

Europe, Middle East and Africa
Alstom Transport
48, rue Albert Dhalenne
93482 Saint-Ouen Cedex France
Phone: +33 1 41 66 90 00

Latin America, Spain & Portugal
Alstom Transport
Paseo de la Castellana 257 -6°
Madrid 28046 Spain
Phone: +34 9 1334 5800

Asia-Pacific
Alstom Transport
24 Raffles Place #27-01
Clifford Centre
Singapore 048621 Singapore
Phone: +65 6220 1138

North America
Alstom Transportation
353 Lexington Ave.
Suite 1100 New York
NY 10016 USA
Phone: +1 607 281 2481

www.transport.alstom.com

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TramWave

Catenaryless power supply system

Robert Vitali
Mass Transit Product Manager
Ansaldo STS

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TramWave solution

TramWave is the key technology to :

- design the future of cities in a “low carbon” scenario.
- maintain and preserve natural or cultural heritage, artistic beauty landmarks and monuments
- make life more pleasant for the residents
- respect the urban legacy and the old buildings near the line
- integrate multi-modal urban transit solutions

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Introduction to TramWave
Characteristics of the application

- **TramWave is an innovative power supply solution designed to minimize :**
  - Visual impact removing the overhead catenary
  - Displacement of utilities (water pipes, gas connectors, electrical grid etc.)
  - Constraints to urban vehicular and pedestrian circulation.
  - Effect of stray currents
  - Pollution
- **TramWave is as solution apt to maximize :**
  - Eco-friendliness
  - Safety (only gravity and electro-magnetic principles), reviewed and validated by TŰV Rhineland
  - Absence of electronics to guarantee safety in all conditions
  - Limited width of the powered section
  - Diagnostic level in all perturbed conditions

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Introduction to TramWave
Characteristics of the application

- **TramWave is a solution designed to be applicable to:**
  - Tram lines
  - Bus lines
  - Special purpose vehicles (utility vehicles, urban maintenance vehicles, etc.)
  - A mix of any of the previous
  - New concept of private vehicle + urban development
- **TramWave is a flexible and modular system designed to be adaptable to a widespread array of configuration and demands of administration and planners**

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Introduction to TramWave
Characteristics of the application

- **Tram application:**
  - Continuous power supply
  - Same level of performance as per traditional catenary (VAC, acceleration, speed etc.)
  - No need of auxiliary systems onboard for autonomous movement
  - TramWave, can virtually be installed on any rolling stock provider
  - Mixed mode power supply. TramWave and traditional catenary (i.e. TramWave in historic or architectural centers, traditional in the suburbs)

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Introduction to TramWave
Characteristics of the application

- **Bus application:**
  - Same level of performance as per traditional buses (VAC, acceleration, speed etc.)
  - Auxiliary systems onboard for autonomous movement off the TramWave sections to overcome obstacles on the line
  - Auxiliary systems onboard for autonomous movement off the TramWave sections even for considerable length, up to 5-6 km
  - Short recharge time on the tramwave line while running (5 minutes per km off TramWave line)
  - Passive self-centering system of the pickup shoe over the TramWave line

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Introduction to TramWave
Characteristics of the application

- TramWave is covered by several worldwide patents owned solely by Ansaldo STS
- TramWave has been implemented in all electric bus version in TRIESTE (Italy)
- TramWave has been revised and assessed by TüV Rhineland
- TramWave has been homologated by the Italian Ministry of Transportation in March 2002

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All Electric Bus TramWave application

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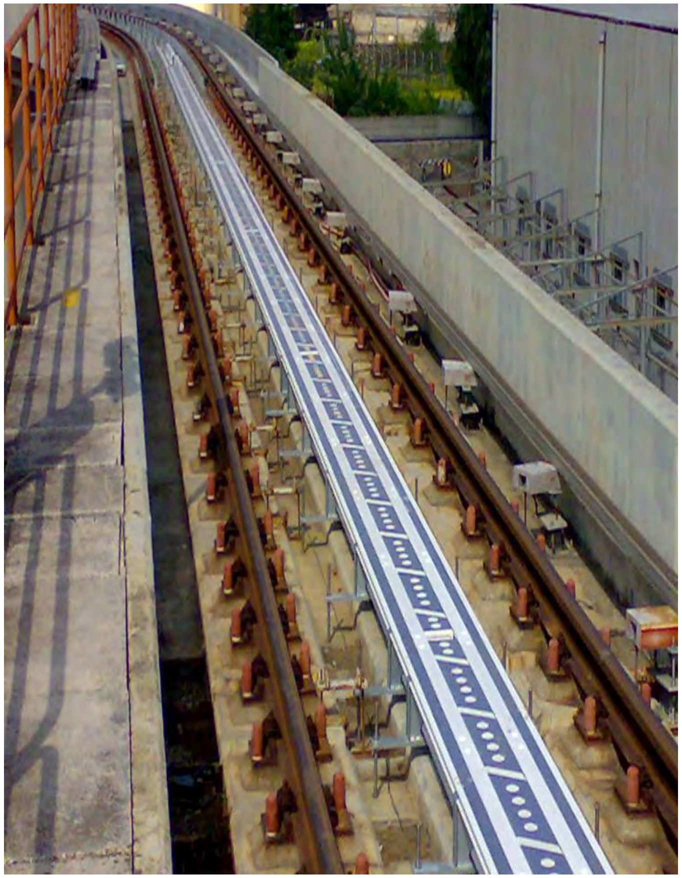
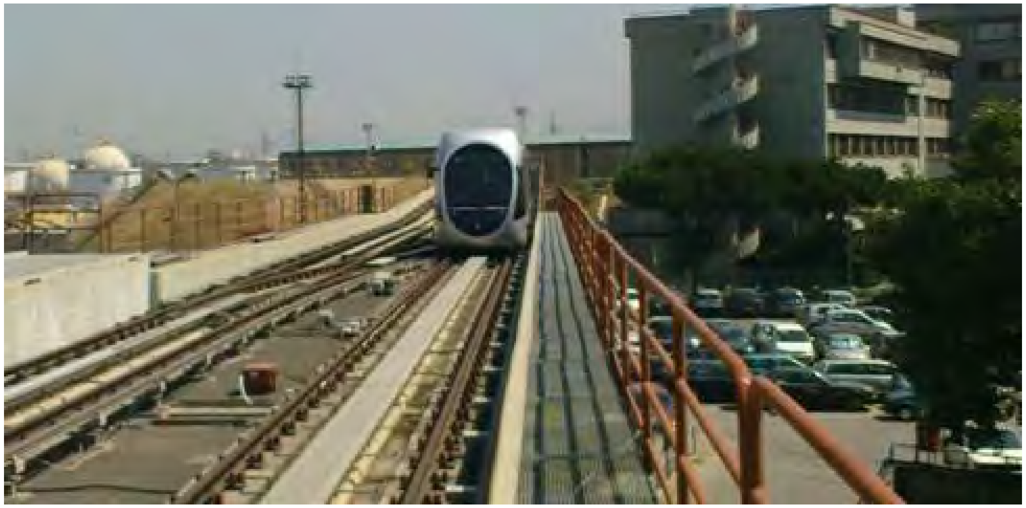
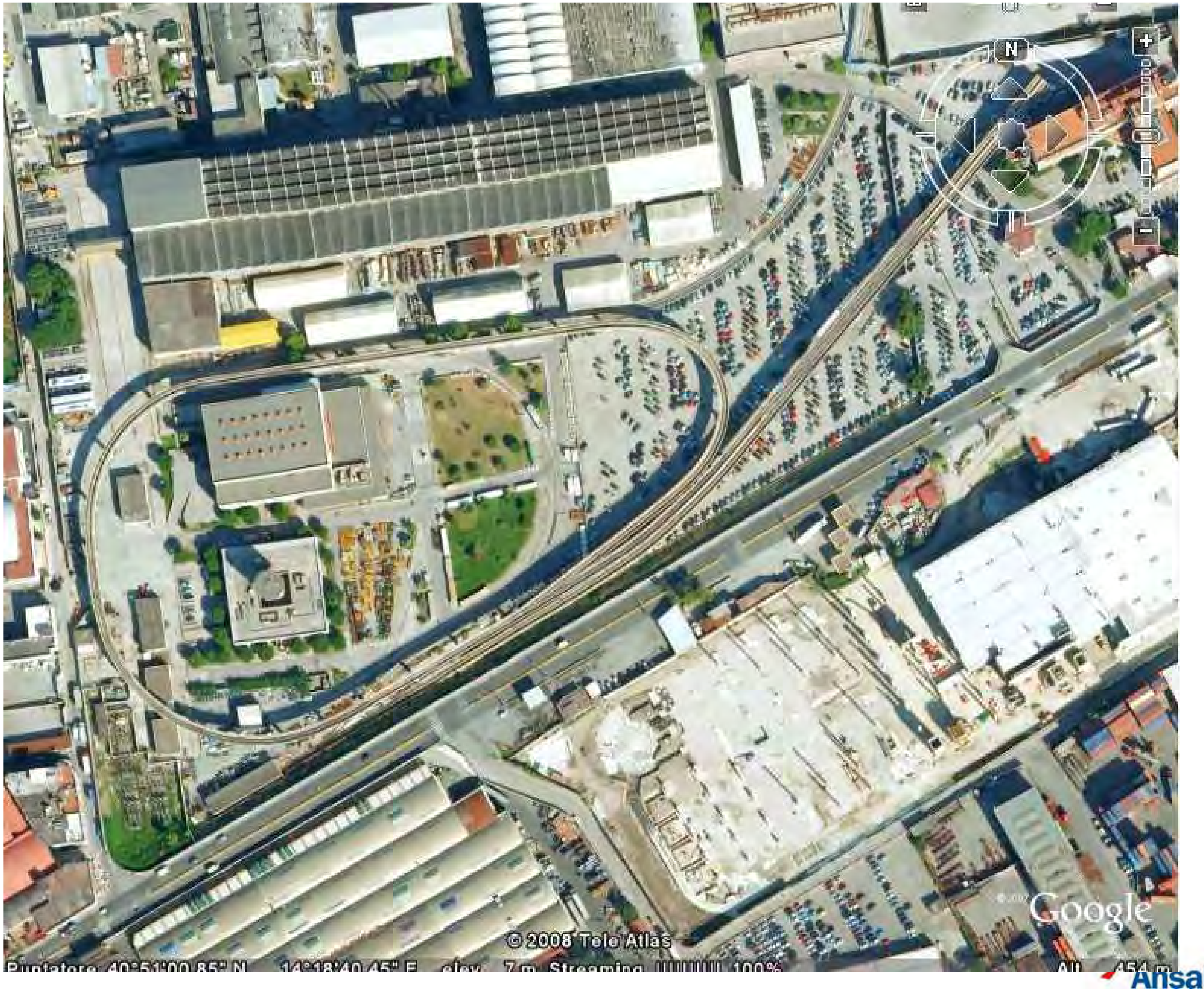
TramWave tram application





TramWave installed on the test track in Naples.
Stress tests for extreme and unusual conditions

Tram application in the test site in Naples


N
© 2008 Tele Atlas
Google
Puntatore 40°51'00.85" N 14°18'40.45" E elev 7 m Streaming ||||||||| 100%
Alt 454 m

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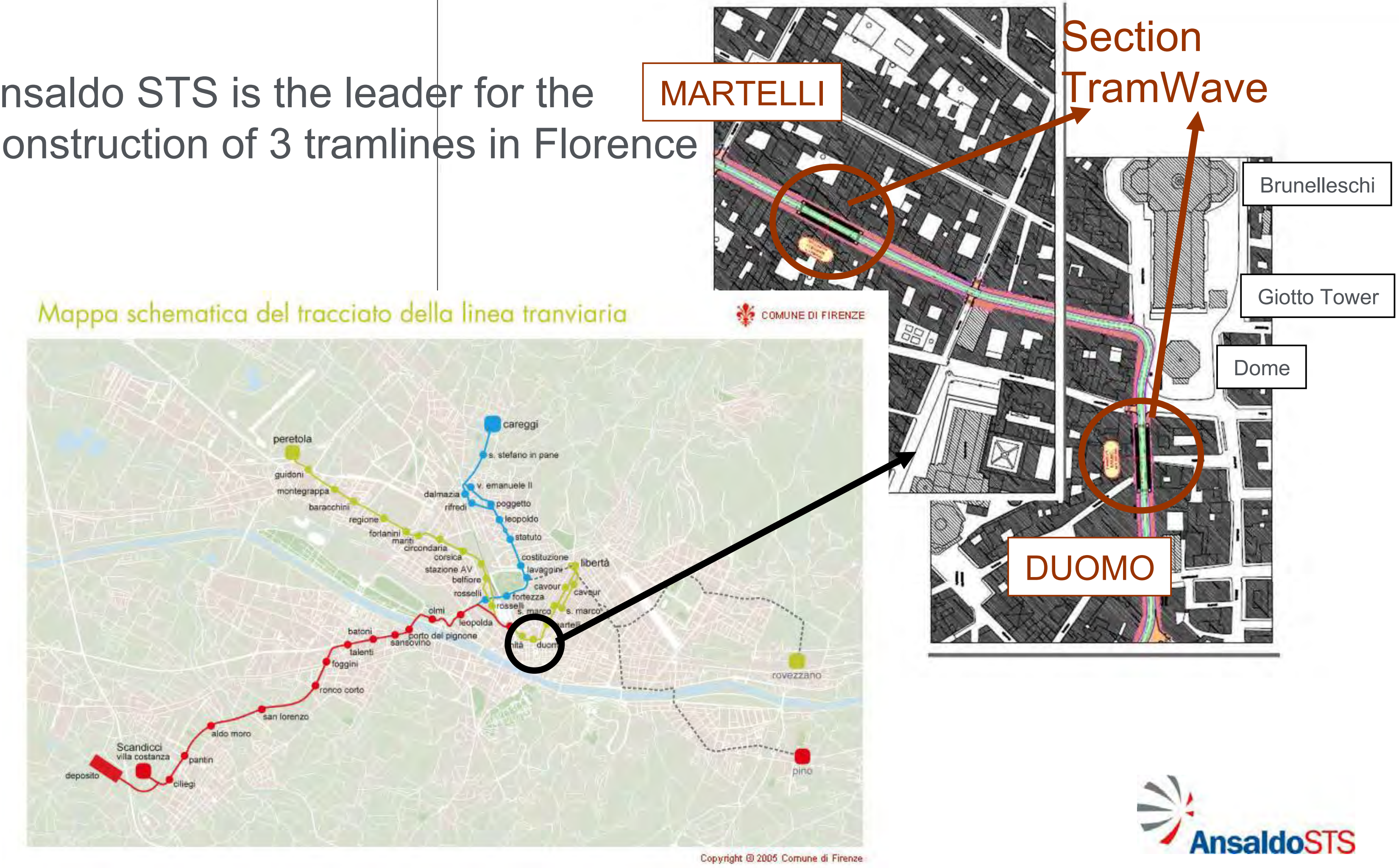
TramWave for Florence

Ansaldo STS is the leader for the Construction of 3 tramlines in Florence



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TramWave Concept

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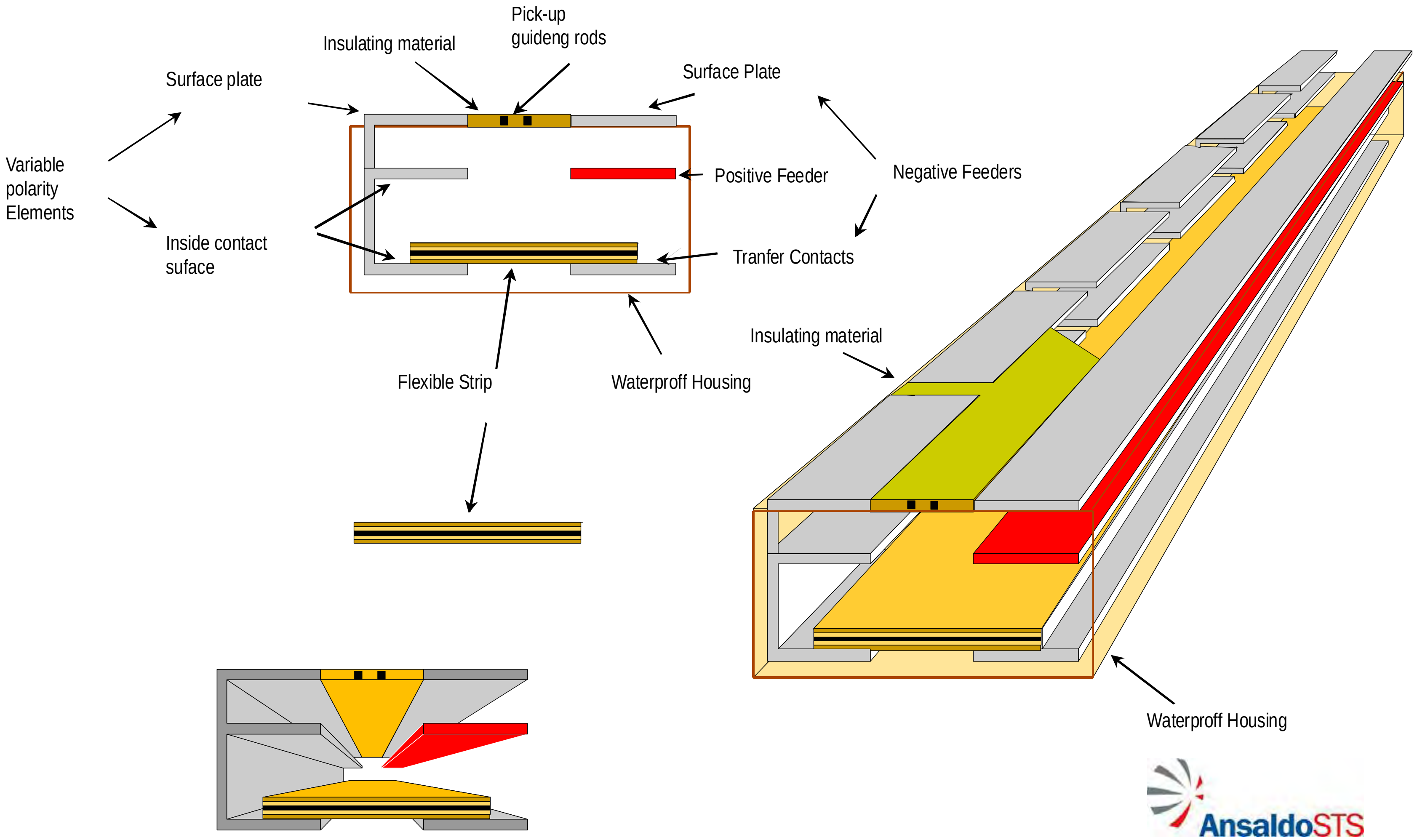
Basic functioning concept of TramWave



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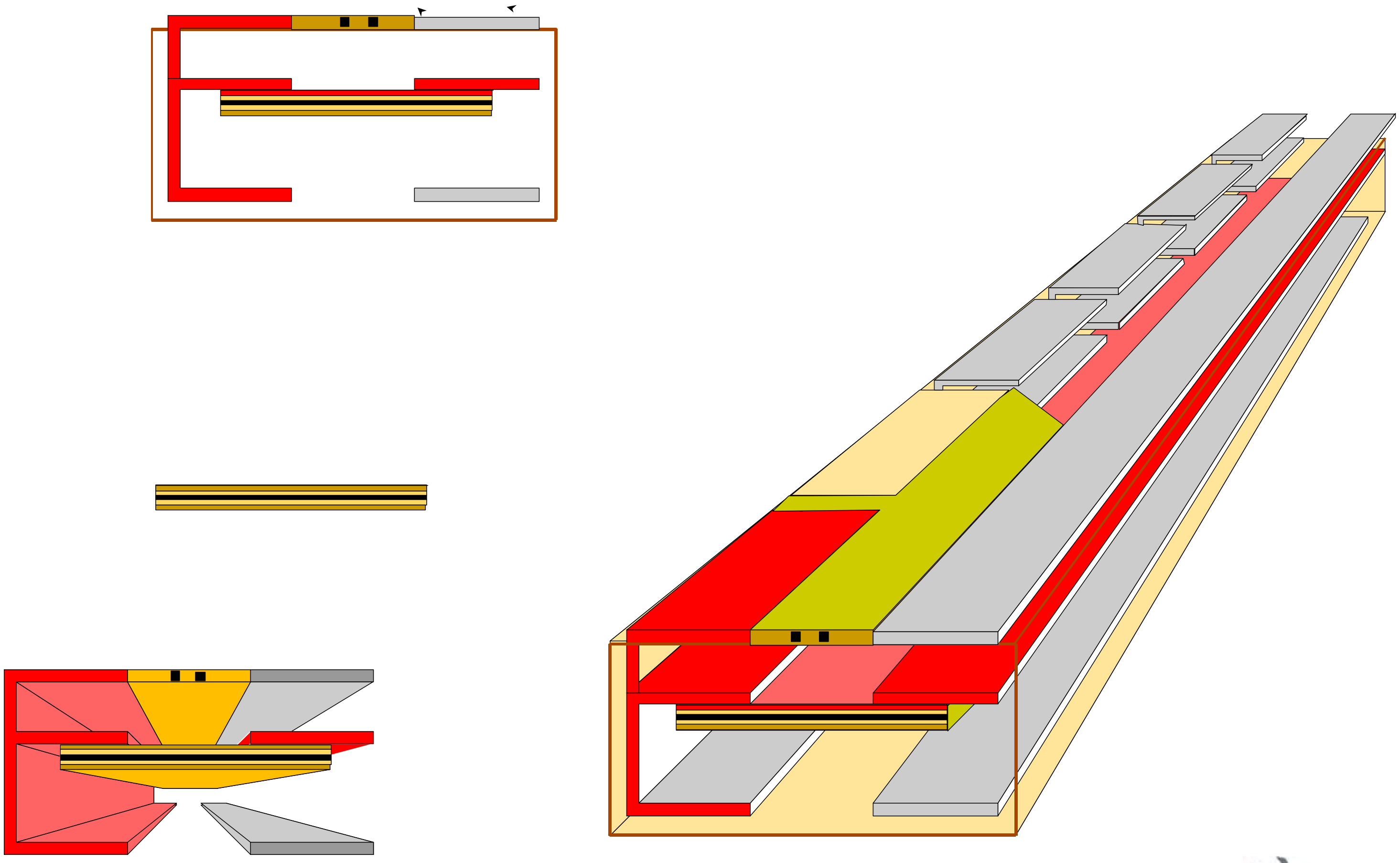
Basic functioning concept of TramWave



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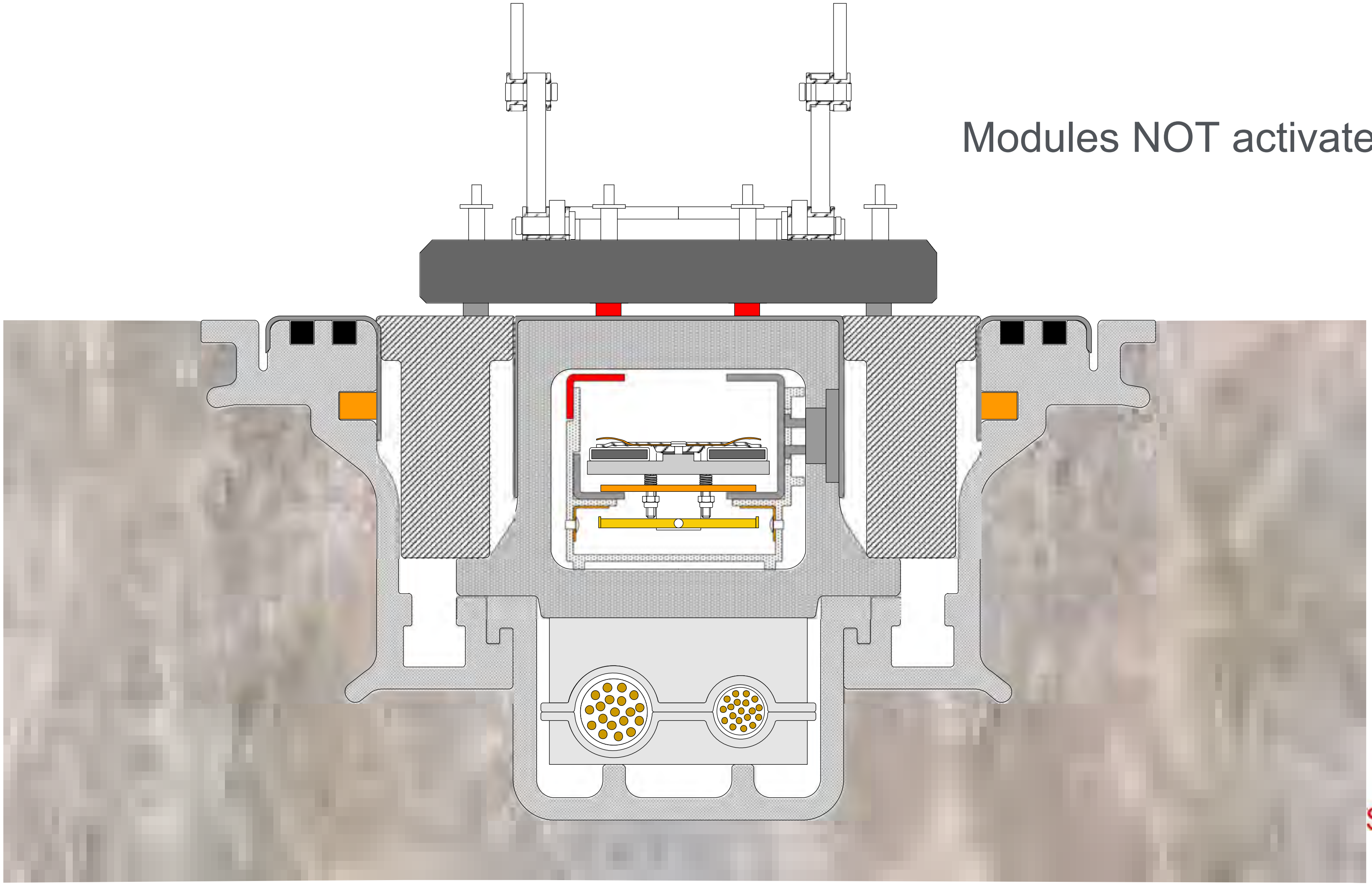
Modules NOT activated



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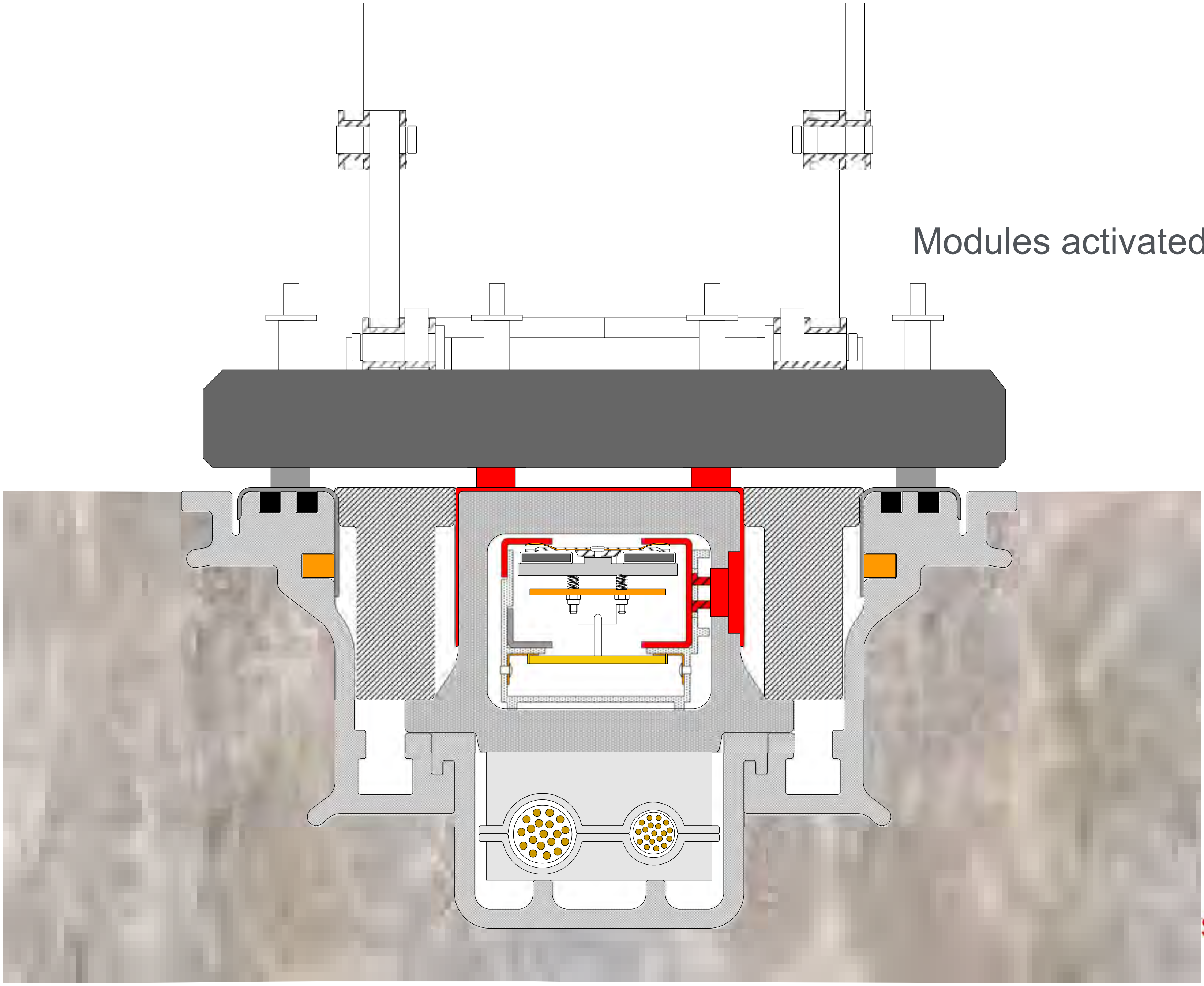
Modules activated



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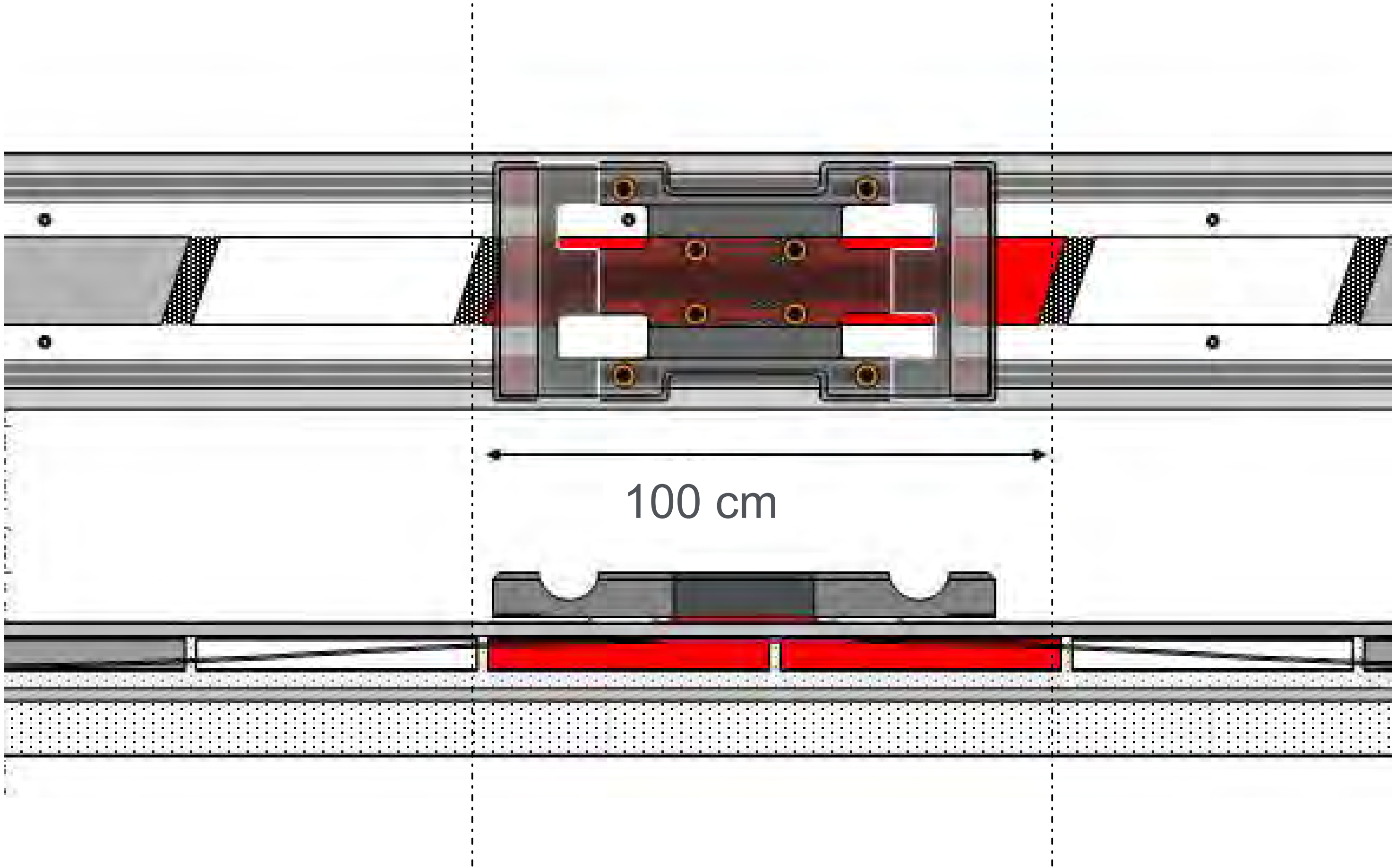
Power collector and activated modules



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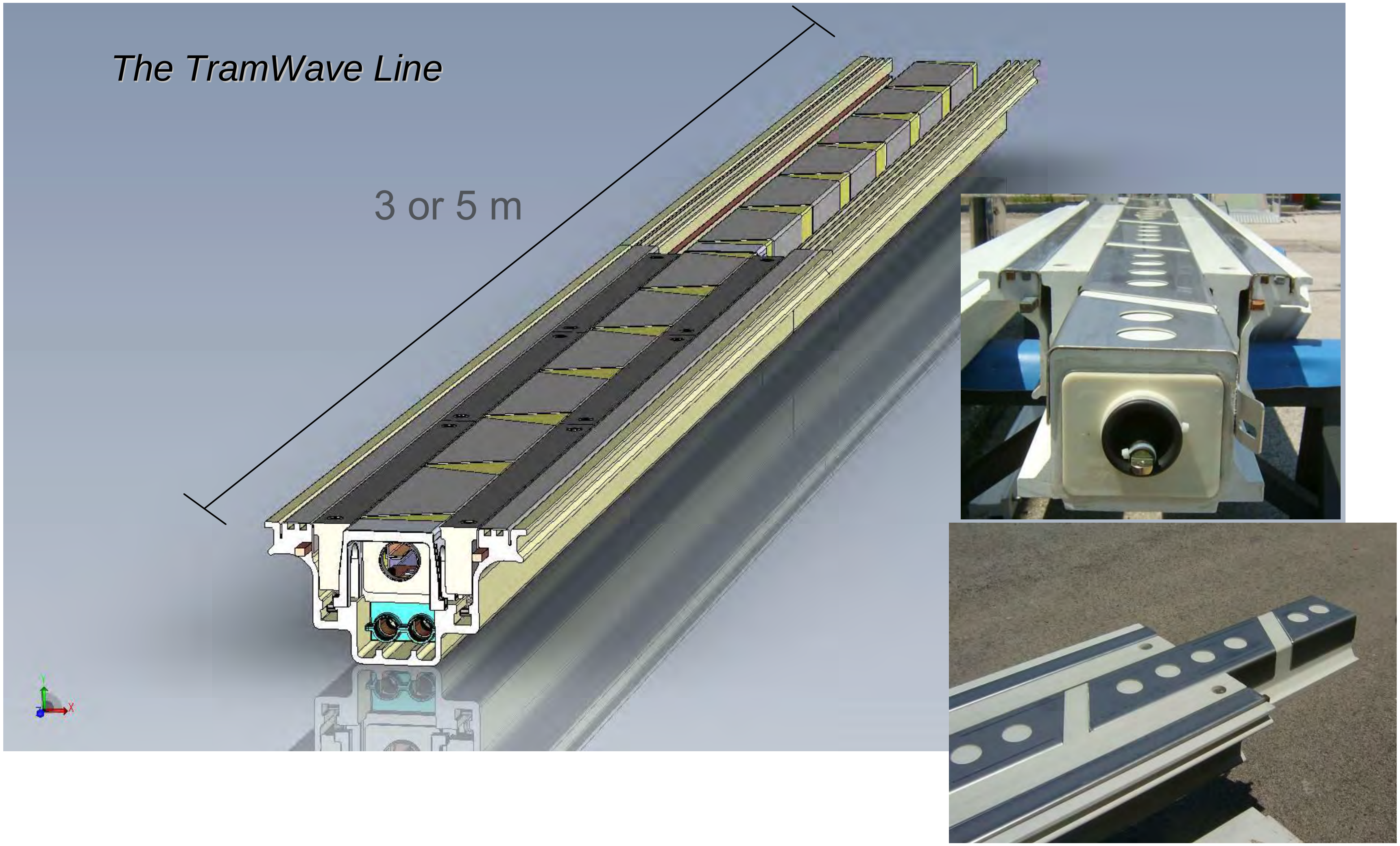
Module layout



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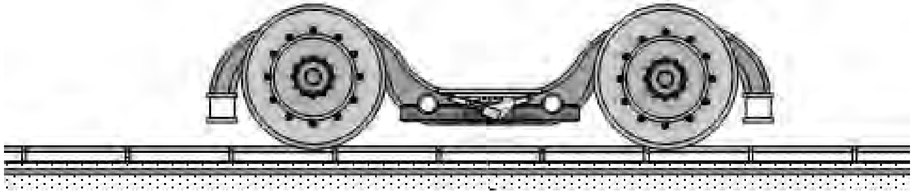
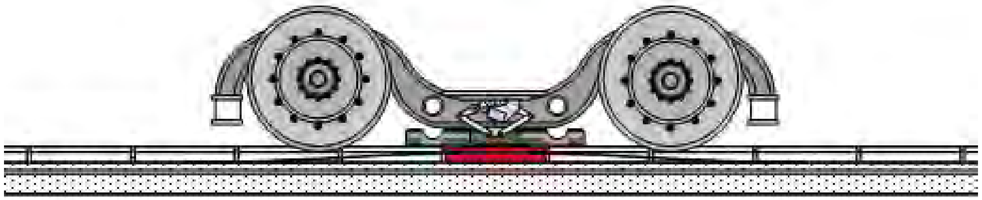


Power collector rest position

- The magnetic power collector in the upper position is unable to activate the power line segments; the pulling force is not enough to lift up the belt.
- The vehicle can run over the line without activating the segments
- All the segments stay connected to ground.

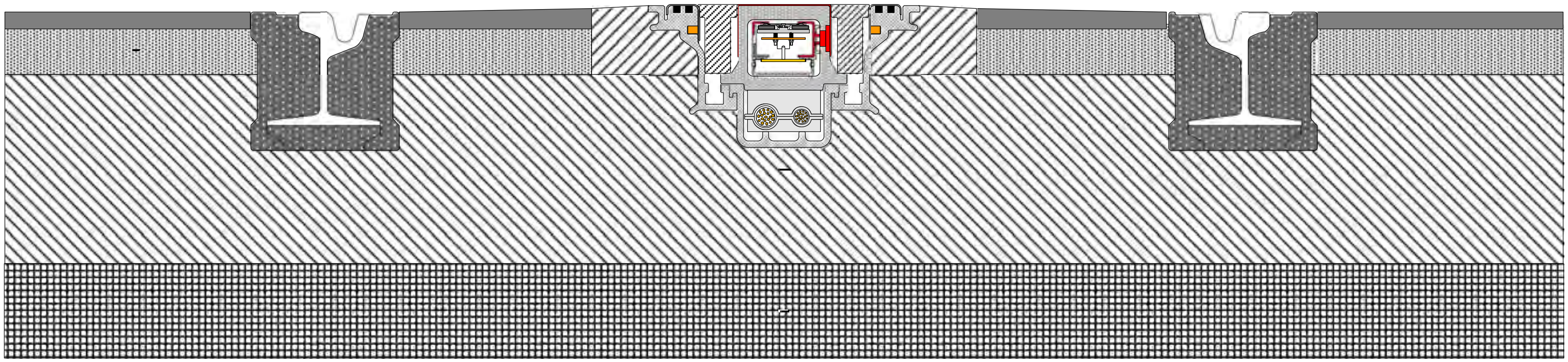


Power collector active

- the power collector is in contact with the line segments
- the flexible belt reaches its working position and activates the underlying segment (s)

TS group

Street level section with the line fully equipped, circulation ready for tram as well as all electric buses



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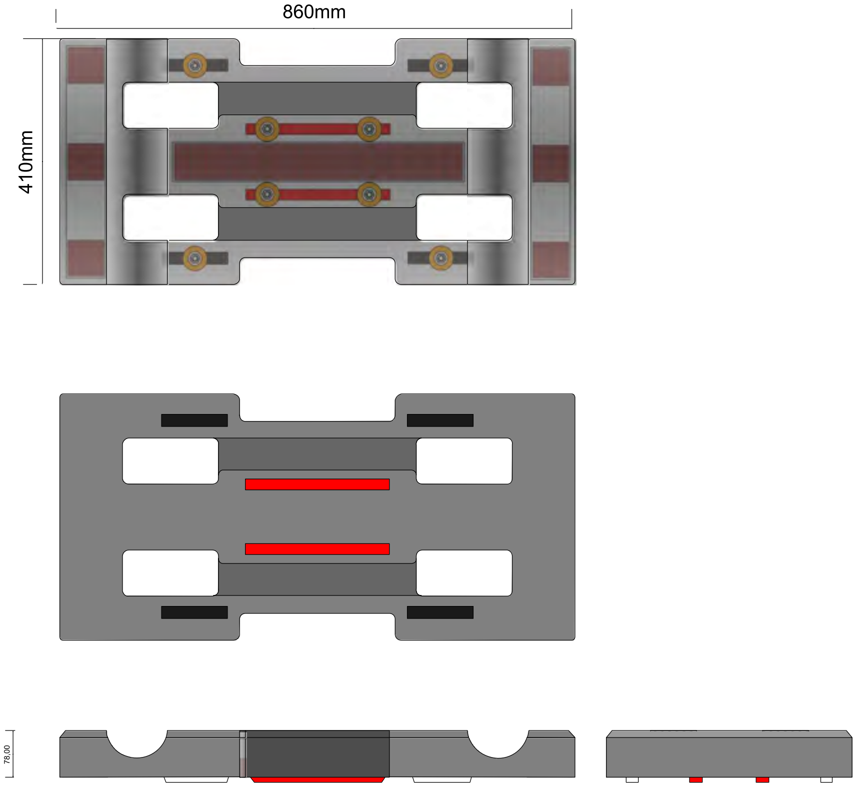
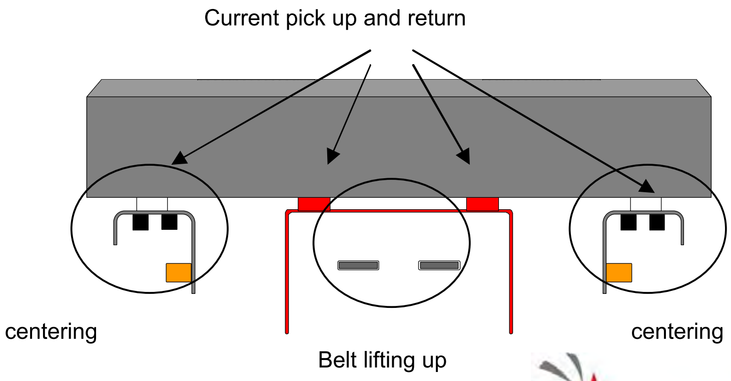
The vehicle magnetic power collector or pickup shoe

Three main functions

- Activation of line segments
- Current pick up and current return
- Guide the power collector over the line





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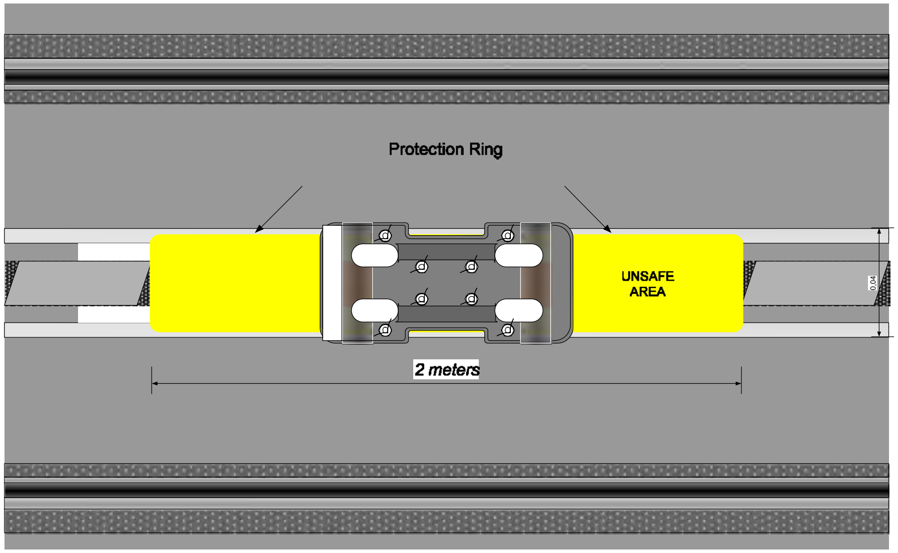
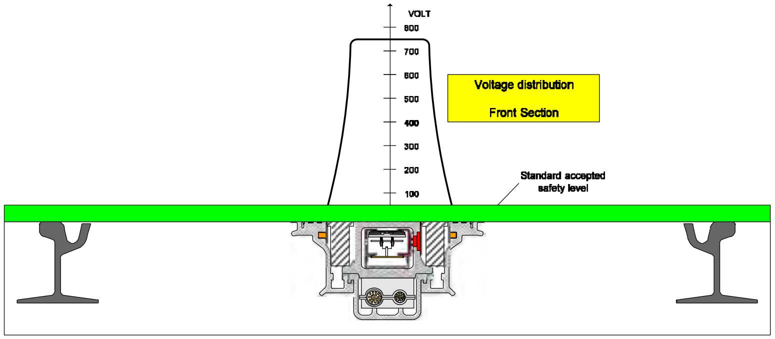
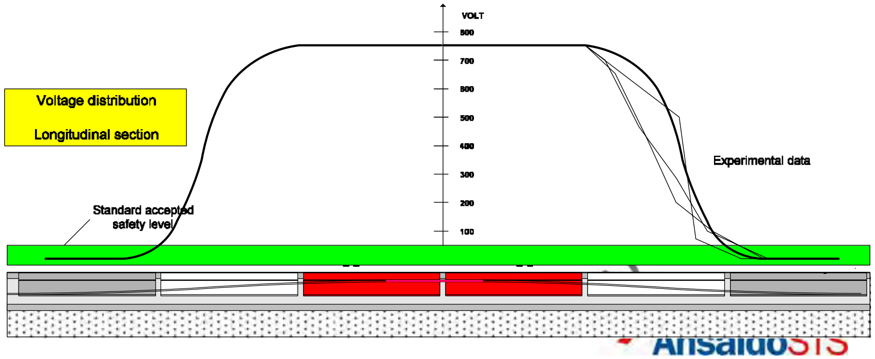
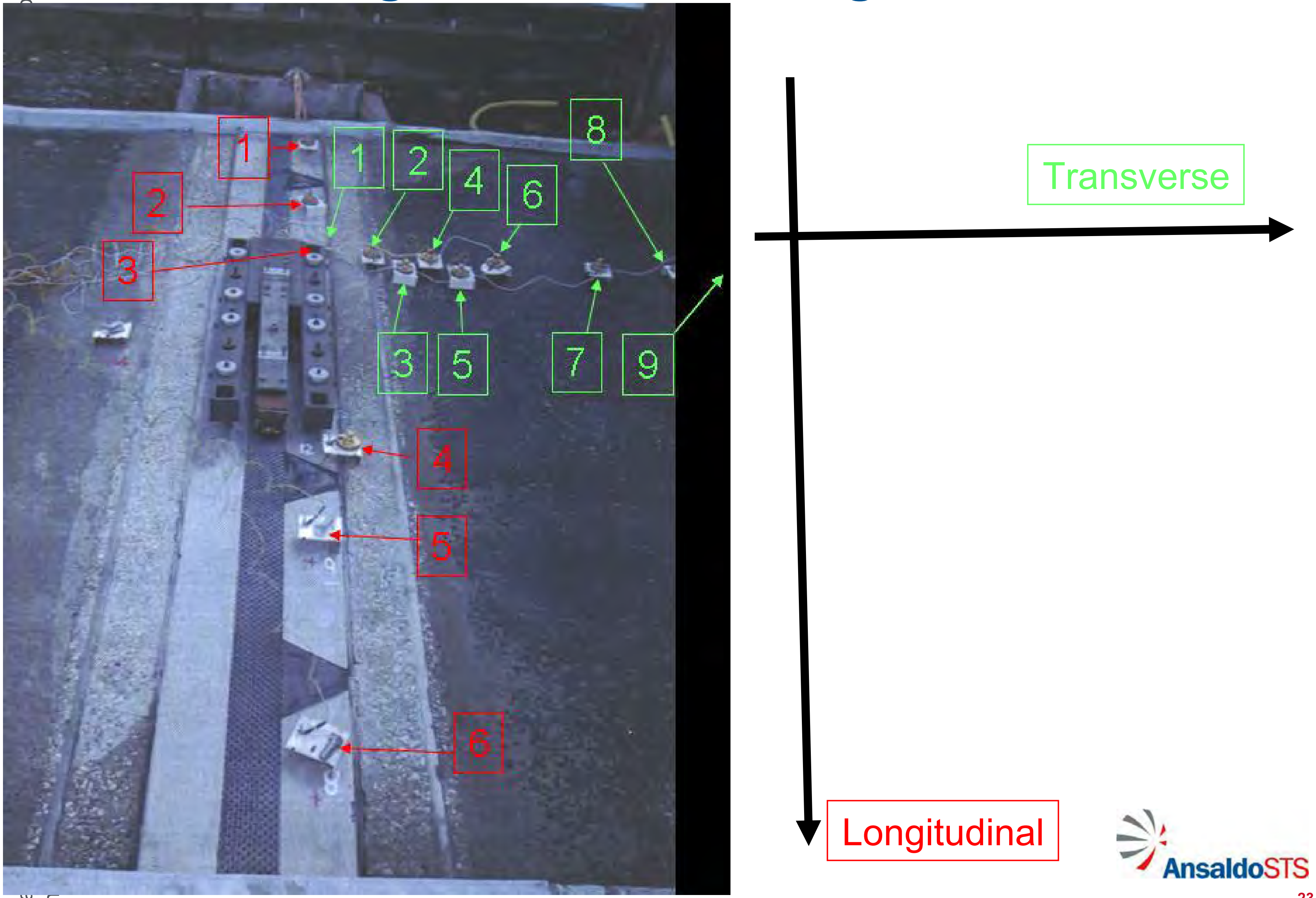
- **The activated part of the line is always enclosed by elements connected to the negative.**
  - These element act as a “Virtual Protection ring”
  - The protection ring follows the power collector .
  - Safety is always assured even in case of water puddles .
  - The running rails act as a second barrier
  - The voltage level all around the activated part remains in any condition lower than the standard requirements.







Voltage disribution along the line



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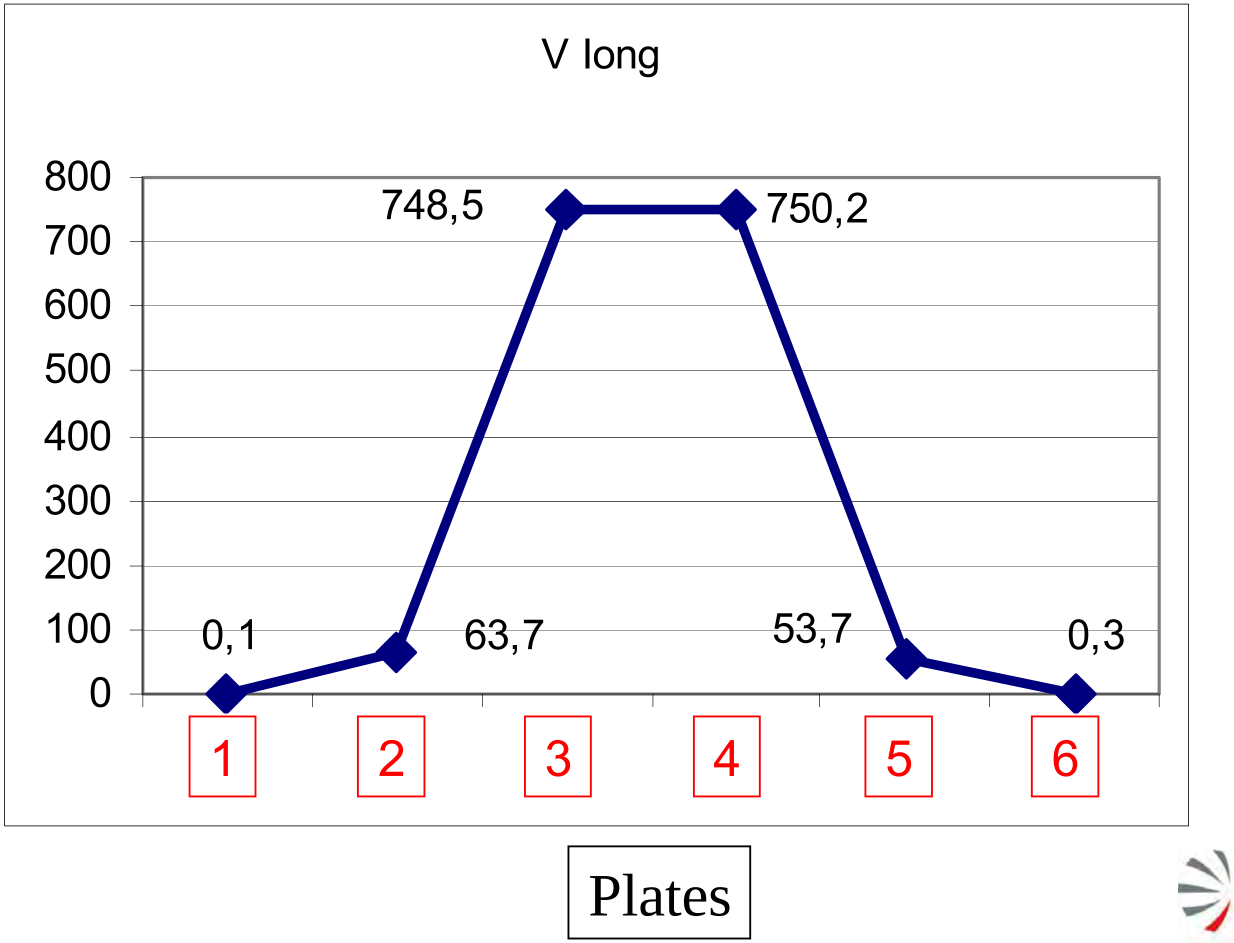
Voltage distribution along the direction of motion



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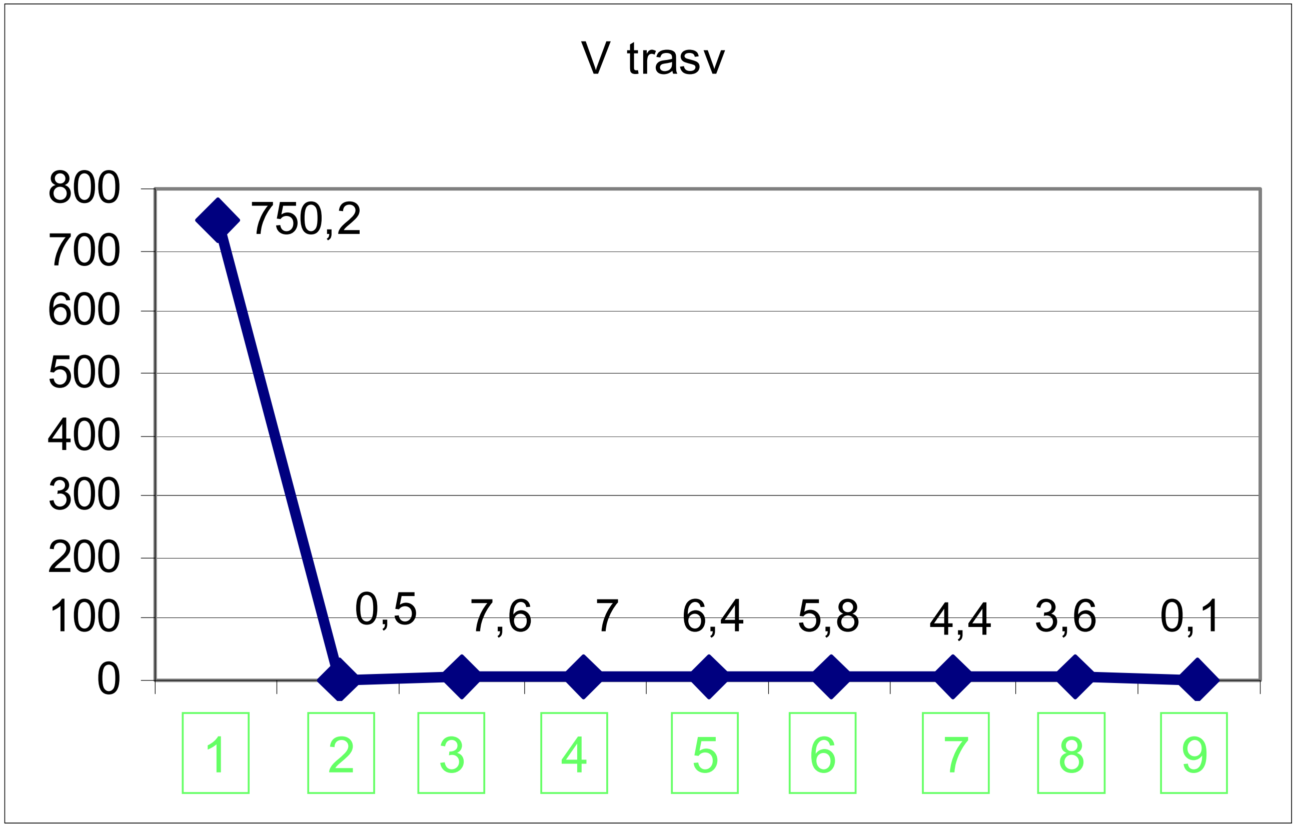
Voltage distribution along an orthogonal direction to the motion



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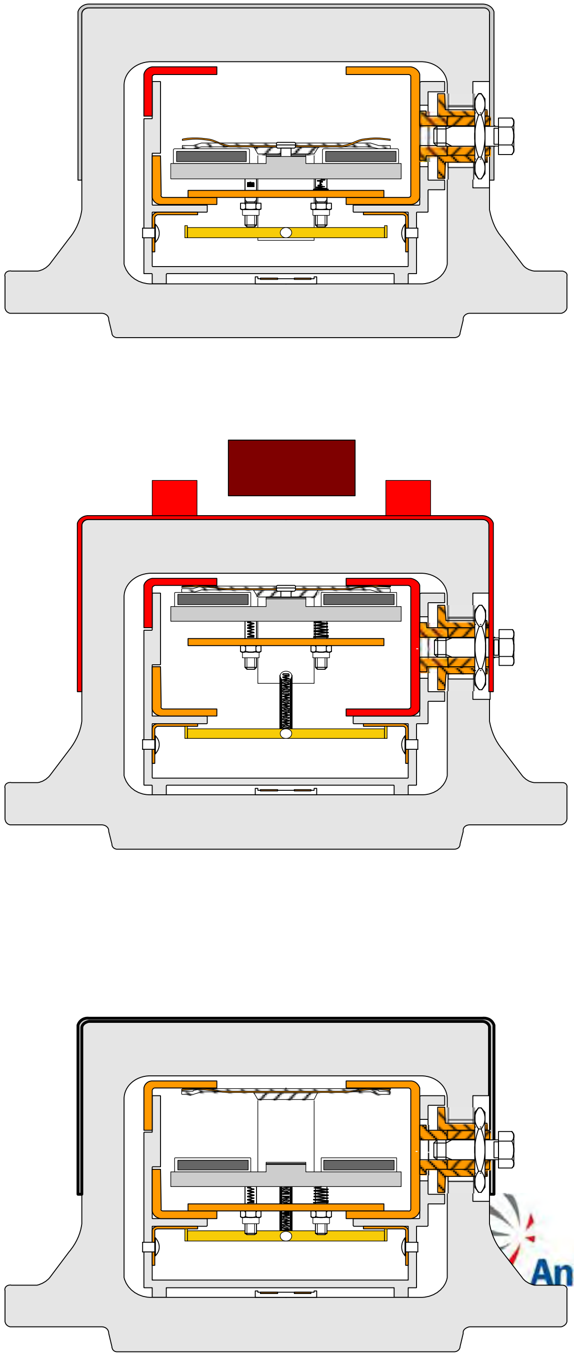
TramWave intrinsic safety concept

- **The design of TramWave assure the safety of the system even in the most severe conceivable accident events:**
  - the “stick” of a positive contact
- **The diagnostic system allows a fast detection of the faulted module.**



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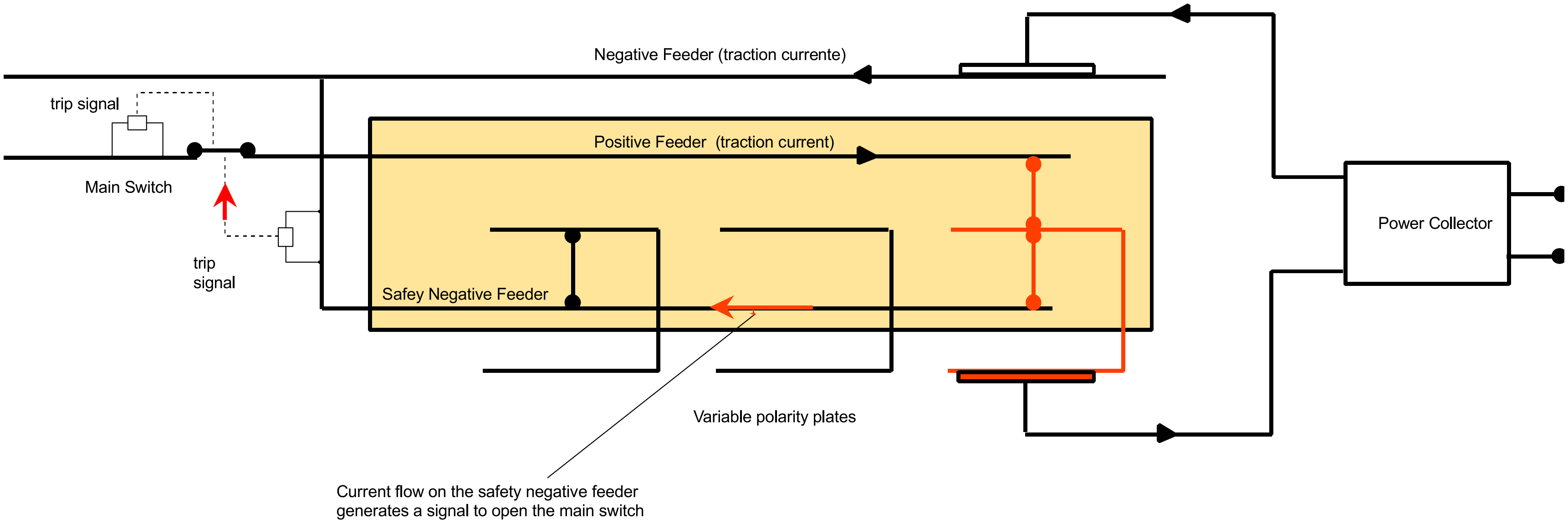
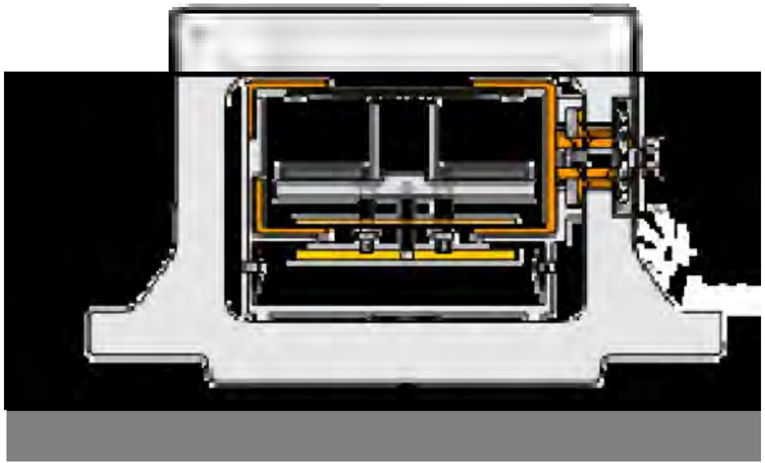
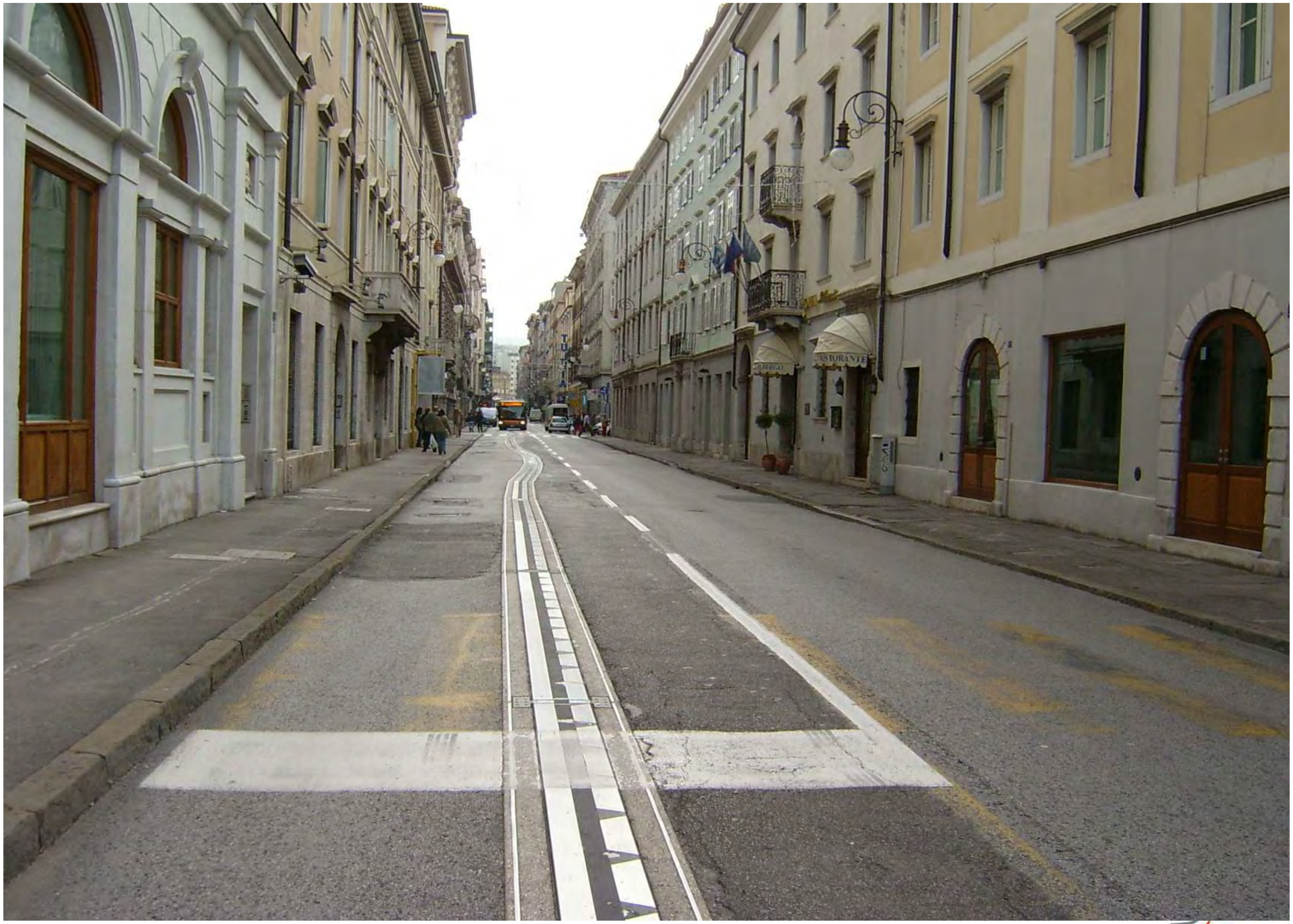

Negative Feeder (traction currente)
trip signal
Main Switch
trip
signal
Positive Feeder (traction current)
Safey Negative Feeder
Power Collector
Variable polarity plates
Current flow on the safety negative feeder
generates a signal to open the main switch

TramWave intrinsic safety concept



TramWave visual impact example



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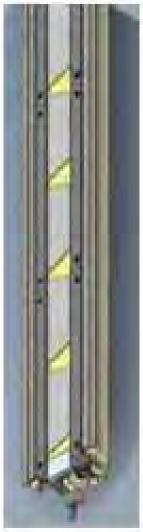
TramWave

ground-level power supply system (no overhead lines)

AnsaldoSTS
A Finmeccanica Company

TramWave

TramWave is a ground-level power supply system for light rail vehicles and trams where the contact line is embedded in the permanent way, so that there are no obstacles to pedestrians and vehicles crossing the rails.
Power is provided via a contact line that only energises a small section of the line as the tram passes over it. the live section of the line is therefore always underneath the tram.
The working range of the tramwave system is up to 750



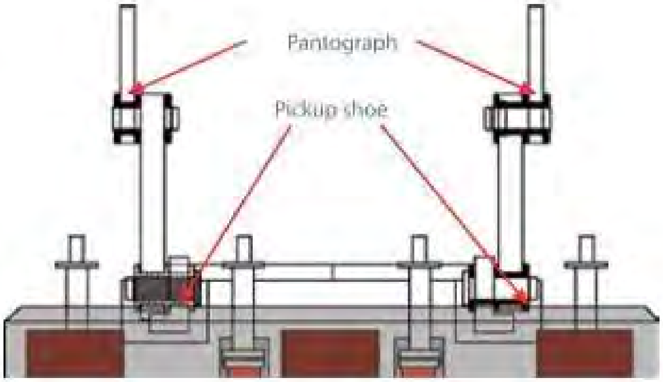
Contact line

The basic building block of the tramwave system is a modular box that is embedded in the permanent way. The box is usually 3 or 5 meters long and it contains all the elements needed for the correct functioning of the ground-level power supply system.
A series of steel contact plates (~50cm) are located at intervals on the top of the box (see figure). the modular boxes are joined together to form the power supply of the light rail line. The modules are placed in a "continuous conduit" that contains the positive feeder and a negative cable to protect the line.

Vehicle pickup shoe

The pickup shoe is the interface between the contact line and the vehicle.
It is placed in the vehicle bogie and its functions are to:
- "energise" one or two of the steel contact plates on the external surface of the power supply "module" located under the vehicle
- transfer energy to on-board equipment

the pickup shoe includes copper and graphite contact shoes and permanent hybrid magnets with high residual induction.

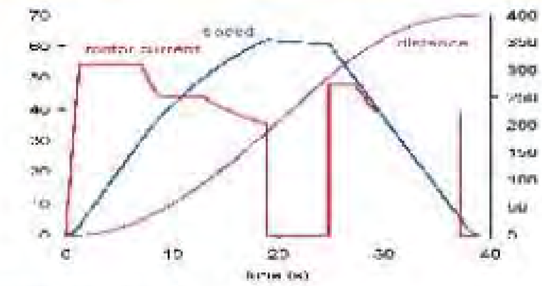


Sirio Tram

City		Nr. of vehicles
Naples		22
Milan II		68
Sassari		4
Gotheborg		40
Bergamo		14
Florence		46
Athens		35
Kayseri		22
Milan I		48

Typical running diagram

speed (km/h) distance (m) current (A)



General Technical Data

Car-body width 2,40-2,60 m
Maximum speed 70-80 km/h
Rail gauge narrow-standard
Bogie power 210 kw
Bogie wheel base 1700 mm

Floor heigh from t.o.r. 350 mm
Consist (3-5-7 casse 2-4 carrelli)
% Motor bogie (50%-75%)
Total capacity 155-285 passengers

Vehicle – Tramwave interface

Vehicles can be retrofitted with a pickup shoe as an alternative or in addition to an overhead pantograph.
The tramwave power collector, which is placed under the vehicle, is interfaced with the vehicle via a hydraulic electrical device and is retractable.
This system allows power to be drawn from the "ground module" continuously at full performance. this is a fully-equivalent alternative to overhead power lines.
An on-board diagnostic system controls operating conditions:

- power collector up
- power collector down

in the case of a mixed traction power supply (overhead and tramwave line), where there is no tramwave contact line the power collector down command is not available.

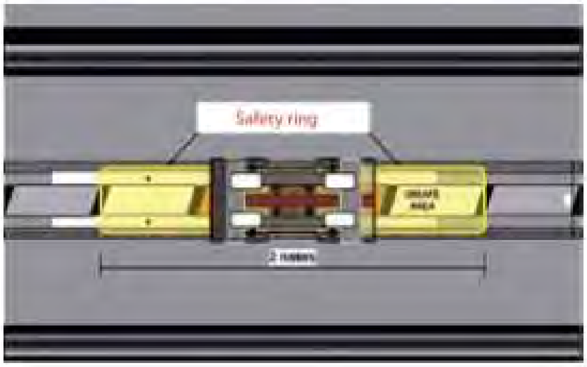
An on-board energy management system can be used to optimise kers (kinetic energy recovery system)performance.

System safety

The safety of pedestrians and the public in general is guaranteed at all times during normal functioning and in any situations where functioning is compromised.

Presence of water on the active module

An earthed "safety ring" is always present around the energised contact plates when the vehicle is moving. this ring comprises the two negative return cables included in the modular boxes and the contact plates above and below the energised plates.



Internal failure

In the unlikely event that a contact plate remains energised after the vehicle has passed, the TramWave system immediately activates a hscb cutting off the power supply.

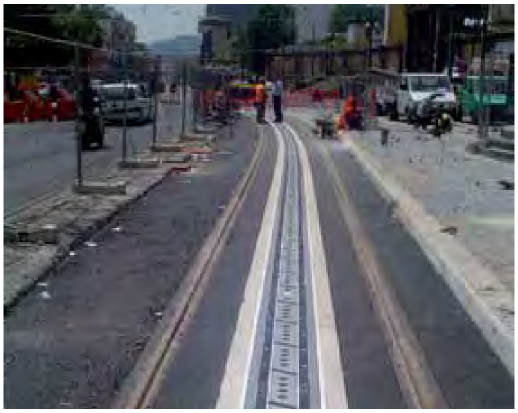
TramWave Performance

With the TramWave system the return current can be transferred via the contact plates and the tracks do not need to be used for this purpose. This is an important feature since the tramwave system eliminates the effects of stray currents, which can offer significant savings on construction costs.

TramWave is also designed for future multimodal applications:
• availability of a positive and negative traction feeder
• capability of the pickup shoe to remain centred and connected to the contact line
these features mean that the power supply system can also be used by electrical vehicles which have rubber tyres. Consequently a tramway line equipped with the TramWave system can become the backbone power line for different vehicle fleets and/or a global network that uses it as a mobile charging station for battery-powered vehicles.

TramWave applications

In Naples Ansaldo factory, a Tramwave line section of about 400 meters has been implemented on the elevated test track.
On this stretch, the TramWave system is being tested under extreme operating conditions.



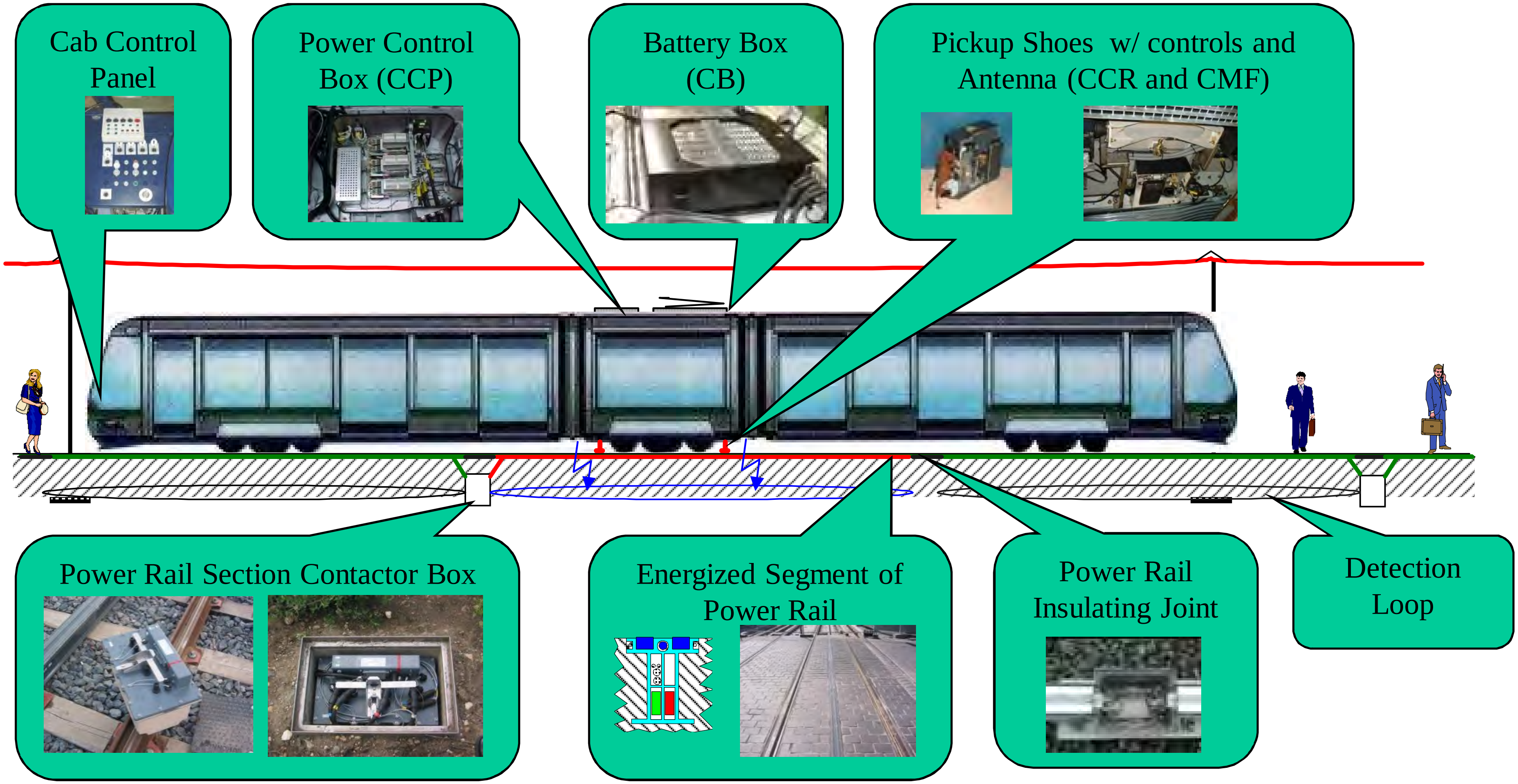
On Naples tram line Poggioreale - via Stadera a trial version of the TramWave system is being implemented on a single track section of about 600 meters.

Ansaldo STS SpA
Via Paolo Mantovani 3 - 5
16151 Genoa - Italy
www.ansaldo-sts.com

A Finmeccanica Company

INNORAIL

INNORAIL System Components



Cab Control Panel

Power Control Box (CCP)

Battery Box (CB)

Pickup Shoes w/ controls and Antenna (CCR and CMF)

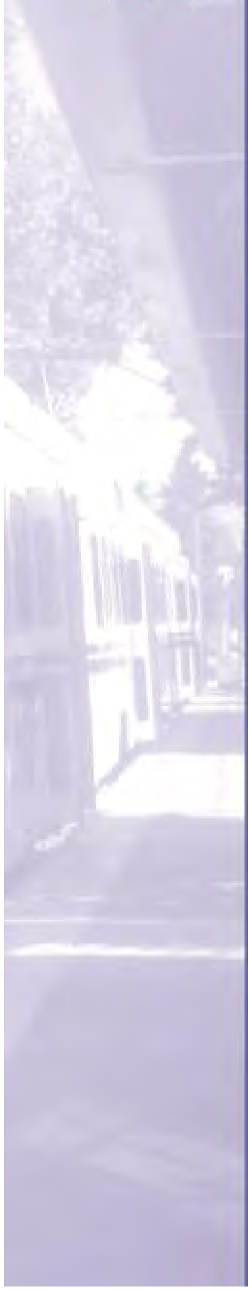
Power Rail Section Contactor Box

Energized Segment of Power Rail

Power Rail Insulating Joint

Detection Loop

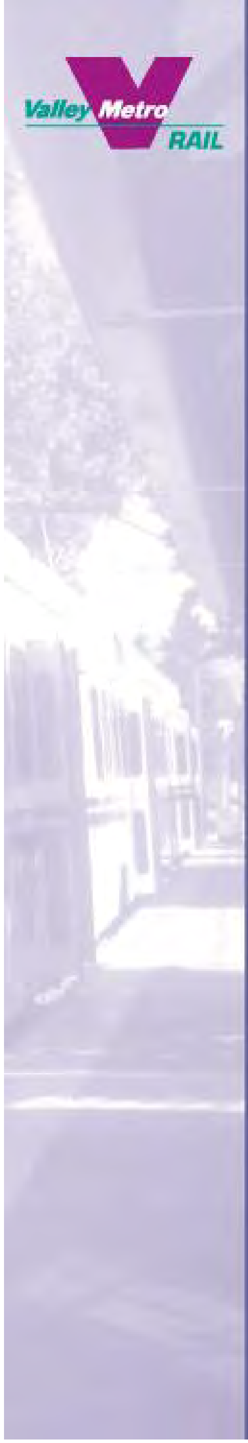
Valley Metro
RAIL



Central Phoenix/East Valley Light Rail Project

INNORAIL Embedded Power System Update

March 03, 2003



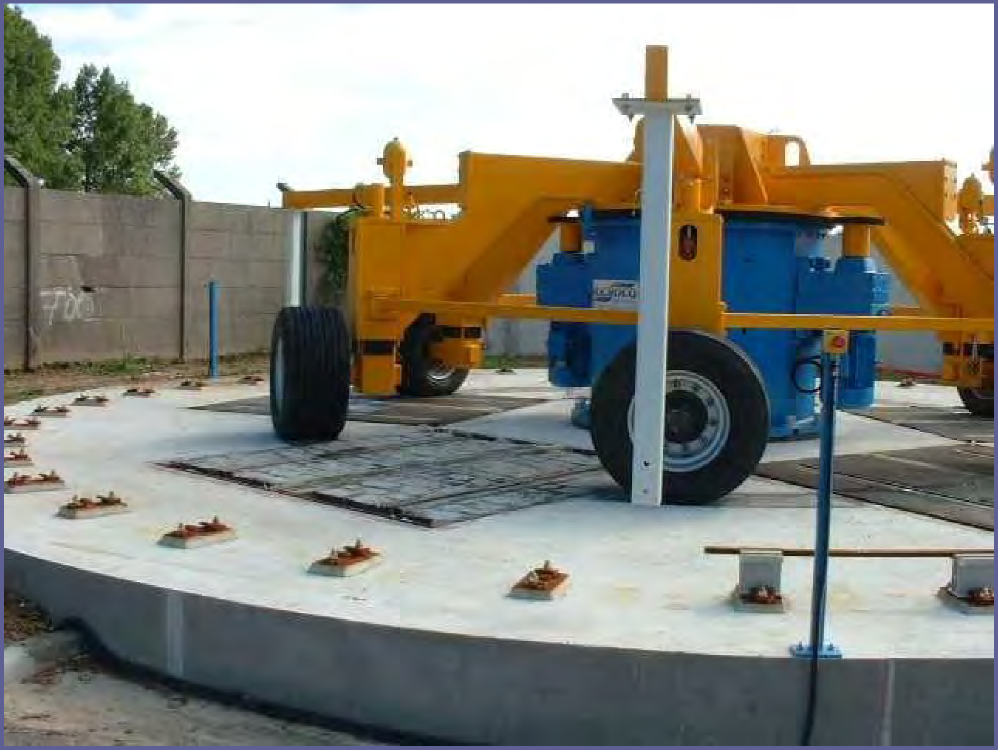
- Following the issue of a CDROM covering recent INNORAIL developments to key Valley Metro staff in November 2002, a technical visit was made by PB personnel to Bordeaux, France from the 17th through the 20th of February 2003 to further evaluate the system on behalf of Orange County Transit Authority (OCTA) with a view to implementing this system in whole or in part in their new LRT system design.
- Given the high level of local interest always shown in having a power supply without overhead wires for the CP/EV LRT system, this system may also be a possibility for this project.

INNORAIL Product Development

- **Prototype Development** – Marseille Line 68 – 1999 – 2001 – with older vehicles at 600 Vdc to prove basic concept

INNORAIL Product Development

- **Endurance Testing** – Ollainville - successful 30 year accelerated test of all embedded components



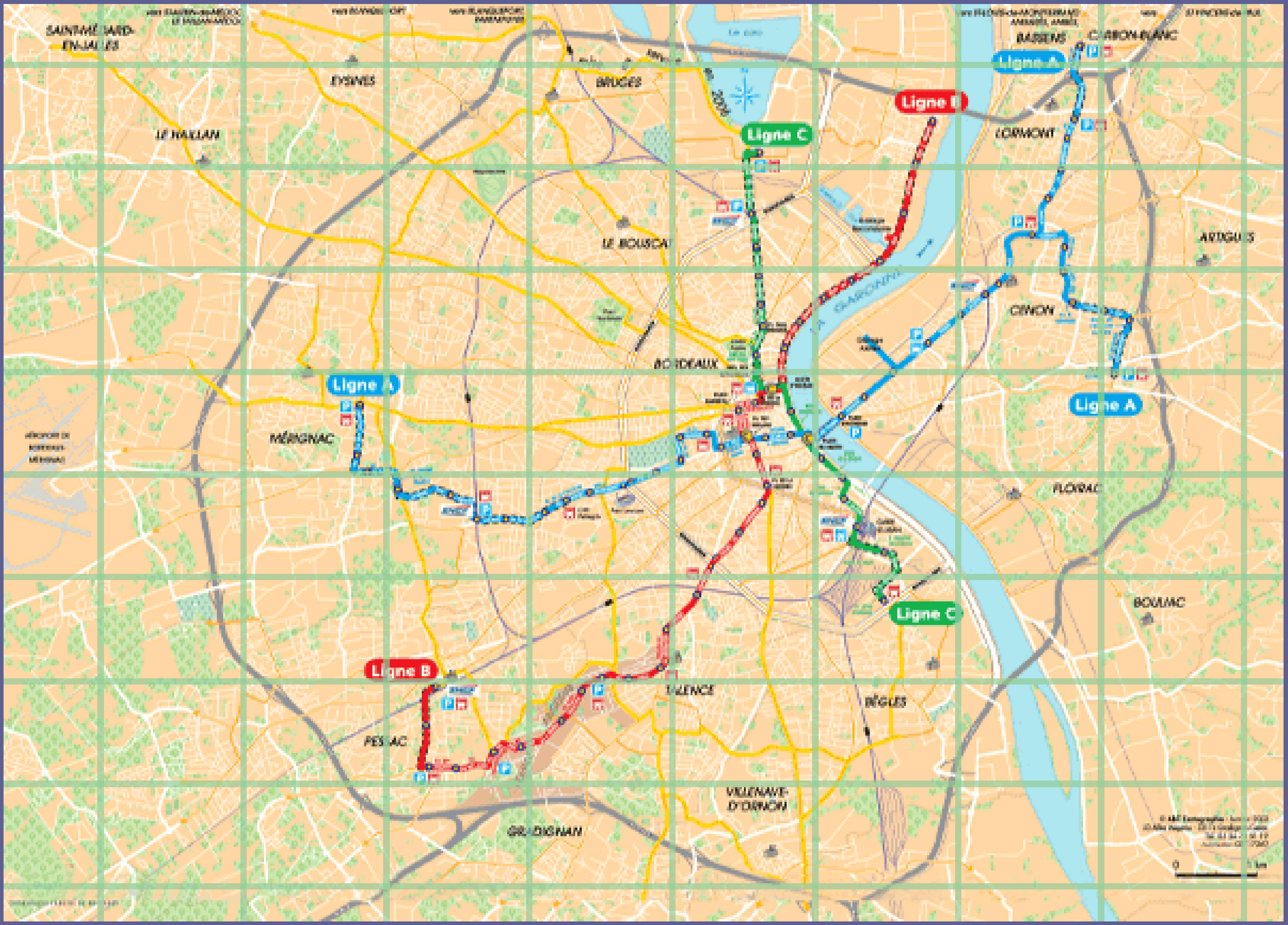
INNORAIL Product Development

- **Continued development** – La Rochelle (Alstom works) - - 2001 to present – test track with modern low floor LRV at 750) Vdc. Over 2000 miles endurance testing plus battery operation and crossing of special trackwork.

The New Bordeaux LRT System

- **Phase 1** – 23.5 km [14.1 mi] long system (Lines A & B) – opens before end of 2003
- In 1999, requirement was for 3 km [1.8 mi] without OCS
- In 2002, decision changed to require 11 km [6.6 mi] using INNORAIL, nearly half the system
- 70 X 100% low floor, air conditioned vehicles running at 4 minute intervals (2 minutes at peak)
- Only single car trains
- **Phase 2** – adds another 20.5 km [12.3 mi] (Line C). Percentage with INNORAIL not yet decided.

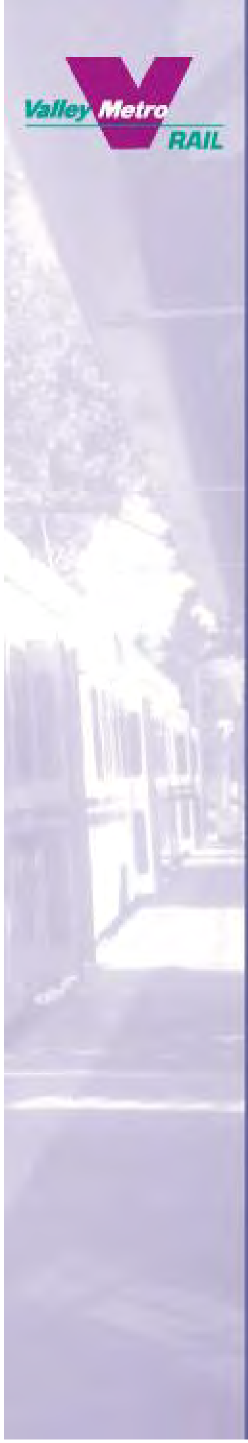
The New Bordeaux LRT System



The New Bordeaux LRT System

The Vehicles

- 6 X 33m long (Citadis 302) and 38 X 44m long (Citadis 402) 100% low floor vehicles in Phase 1
- 12 X 33m long (Citadis 302) and 14 X 44m long (Citadis 402) 100% low floor vehicles in Phase 2



The New Bordeaux LRT System

Additional Vehicle Equipment for INNORAIL Operation

- One roof mounted **Emergency Battery Set** to allow vehicle to transition any dead power segments
- Two sets of center truck mounted **Retractable Power Pickup Shoes** for current collection
- One **Pickup Shoe Control Box** to activate pickup shoes and interlock with pantograph controls
- One roof mounted **Power Control Box** with additional contactors and controls for switching power from pickup shoes and emergency battery set

The New Bordeaux LRT System

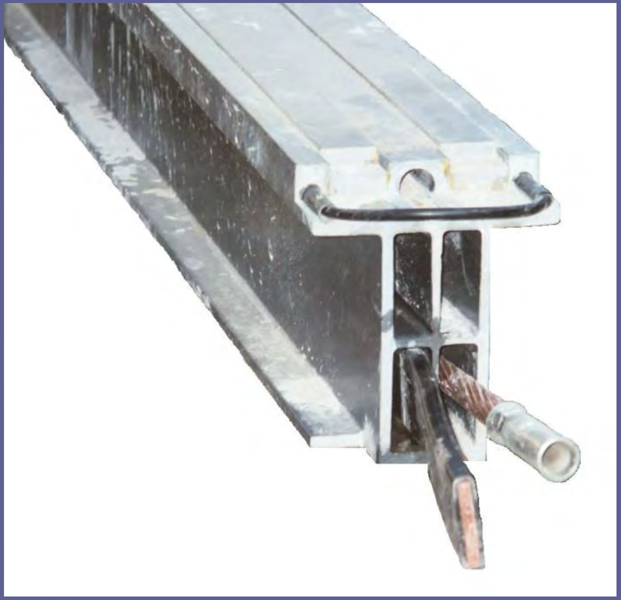
Additional Vehicle Equipment for INNORAIL Operation, cont’d.

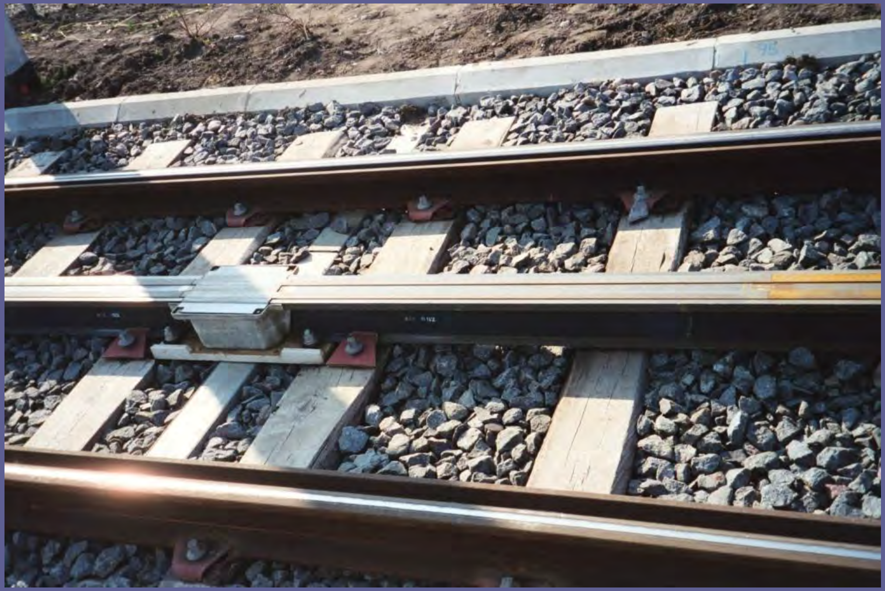
- Additional Cab Controls and Monitoring to monitor and control INNORAIIL related equipment
- Additional Safety Earthing under low floor section of vehicle

The New Bordeaux LRT System

Ground Level Equipment for INNORAIL Operation

- Low profile, sectional **Power Rails** - 11m [36 ft] long sections with 8m [26.25 ft] of conductor rail and 3 m [9.84 ft] of insulating rail with integral duct bank and detection loop

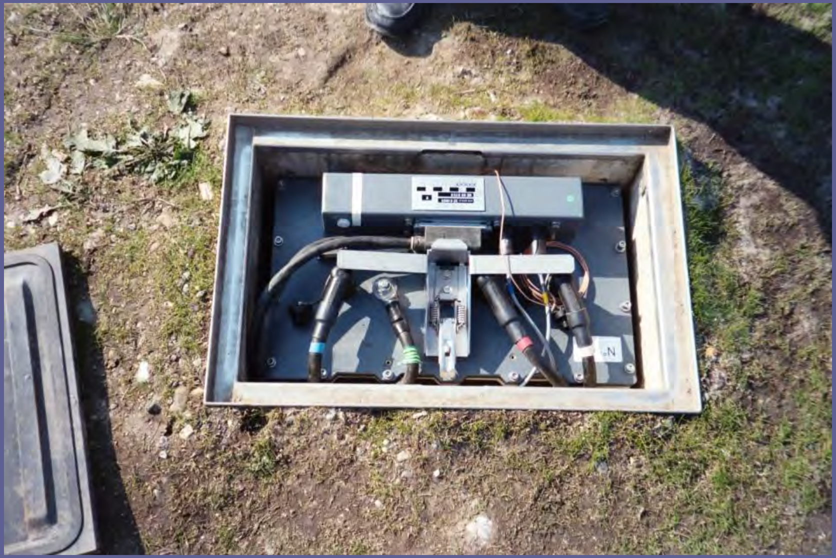




The New Bordeaux LRT System

Ground Level Equipment for INNORAIL Operation

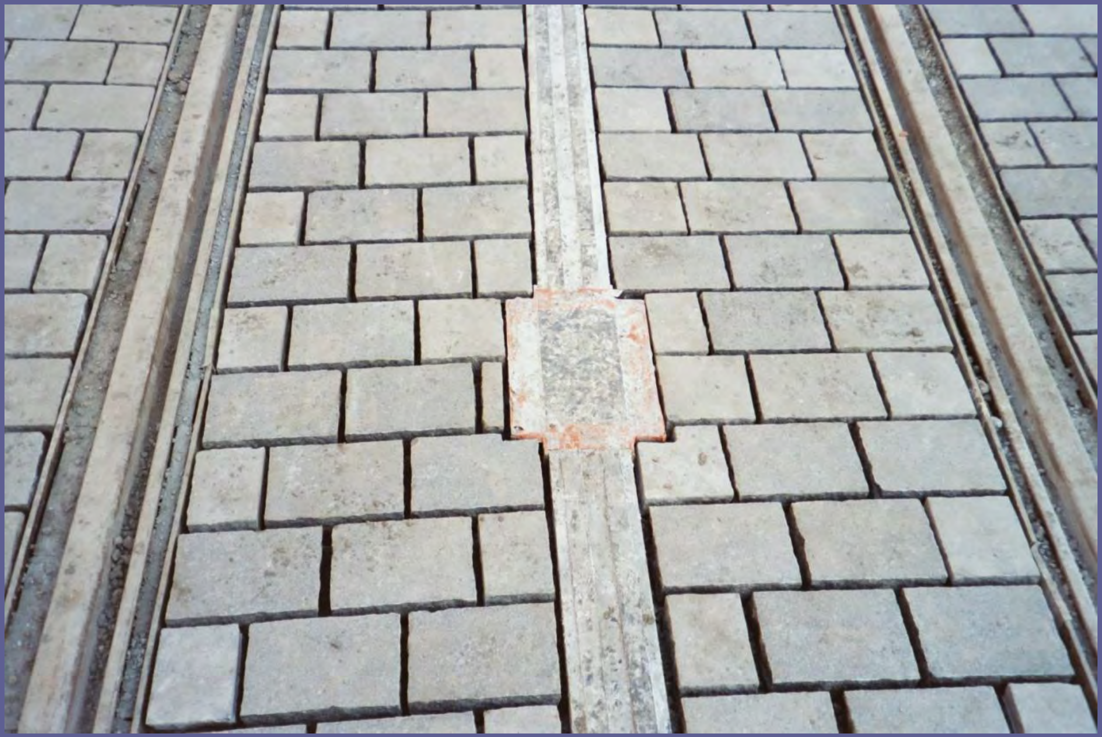
- Modular, quick replacement **Power Rail Control Contactor** - one every 22m [72.2 ft], controls two segment of power rail



The New Bordeaux LRT System

Ground Level Equipment for INNORAIL Operation

- **Insulating Joint Box** one every 22m [72.2 ft]



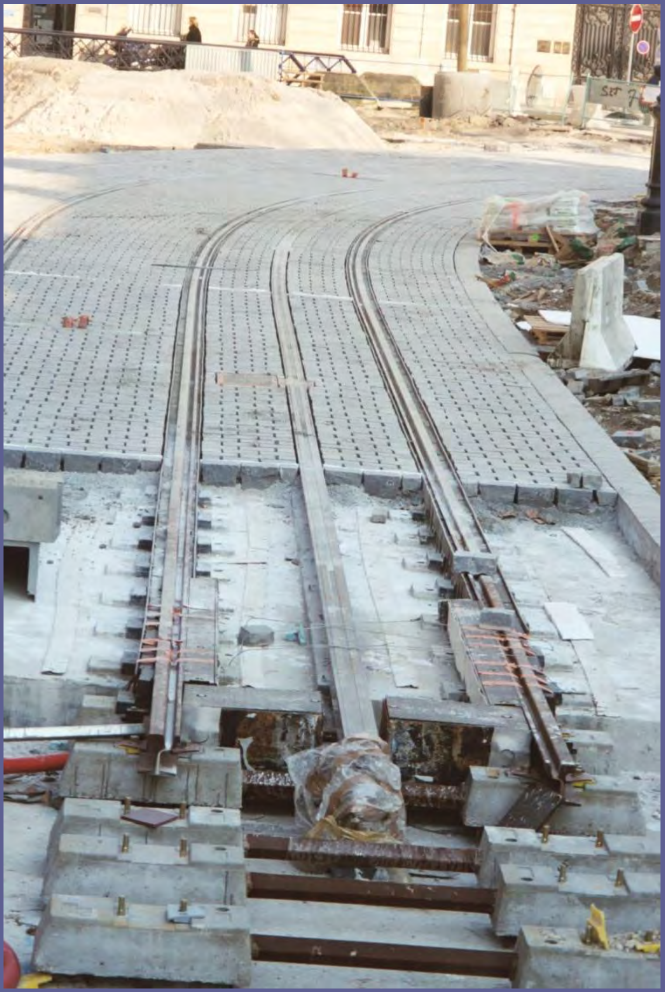
The New Bordeaux LRT System

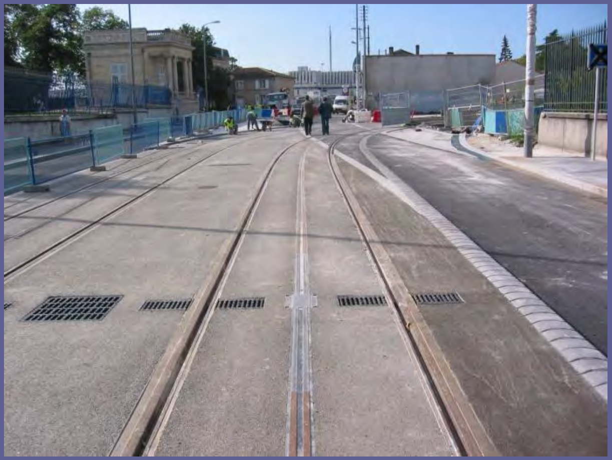
Ground Level Equipment for INNORAIL Operation

- Substation **Earthing Contactor and System Monitoring Cabinet** – one per substation

The New Bordeaux LRT System

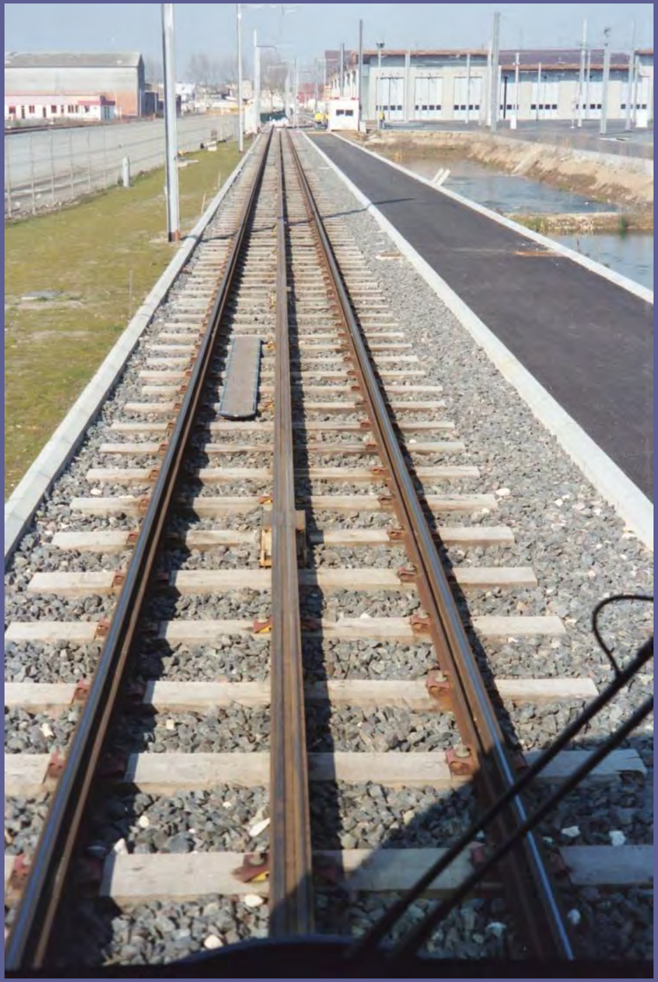
Ground Level Equipment for INNORAIL Operation





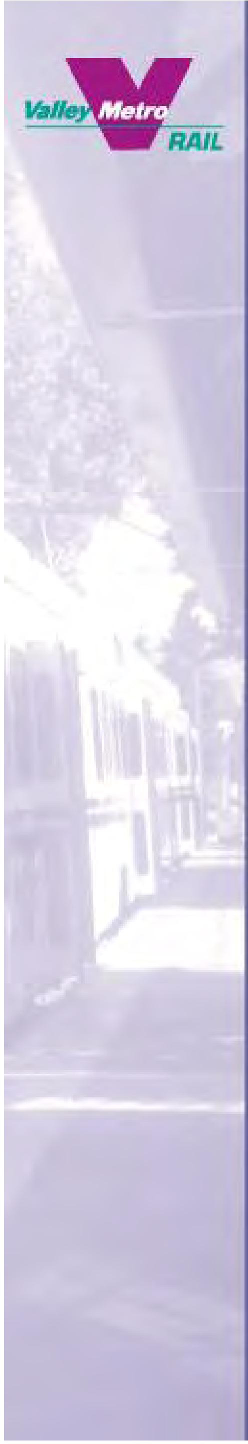
The New Bordeaux LRT System

Depot Test Track



The New Bordeaux LRT System

Coming Soon



The New Bordeaux LRT System

Safety and Certification

- **Being independently assessed to EN 50126 –** *Railway Applications – The Specification and Demonstration of Availability, Maintainability and Safety (RAMS*) **and ENV50129 –** *Safety Related Electronic Systems for Signaling*
- **Preliminary Safety Case approved January 2000**
- **System Safety Case 85% complete and awaiting energizing of complete system in summer of 2003**

Adapting the INNORAIL System to US Requirements

- The INNORAIL system concept is well designed with no “Fatal Flaws” and adequately mitigates identifiable safety hazards, thus Safety Certification in the US should be achievable.
- Such certification will require considerable preparation and documentation to be presented to the local certifying authorities, but can build on the experience of the Bordeaux certification process.
- Adapting for multi-car operation – this is readily achieved by increasing the size of the main power bus

Adapting the INNORAIL System to US Requirements

- Adapting for higher speeds – the current system is designed for a speed of 20m/sec [44.7 mph] . Relatively minor changes in the relative lengths of the conducting and insulating rails will easily allow for higher speeds where required
- Product Availability – INNORAIL currently being sold to Alstom. Willingness of Alstom to provide this system for the US market or license same not yet known.
- Sole sourcing – the technology is proprietary, thus sole sourcing would be required. This is allowable under FTA C4220.1D.

Adapting the INNORAIL System to US Requirements

- **Buy America – many of the system components can be manufactured under license in the US**
- **Adapting for gradients – given the relatively steep gradients on the CP/EV LRT system at the Washington Street underpass and coming out of the Maintenance Facility, a larger set of batteries will be required for the Emergency Battery Set, adding to the vehicle cost and weight**
- **Adapting for US LRVs – universal nature of additional vehicle equipment will allow fitting to any modern low floor LRV**

Adapting the INNORAIL System to US Requirements

- Cost – based on current Bordeaux prices, it is estimated that the cost will be $1.6 to $2.0 million per double track mile for the embedded power rail, plus $40,000 per substation for the earthing contactor and monitoring equipment , plus $129,000 to $161,000 per LRV for the additional INNORAIL related vehicle mounted equipment.
- Other US systems – none as yet, but Orange County (OCTA) seriously considering system and Honolulu has also expressed interest. Once availability of system known, demand will increase dramatically.

Valley Metro RAIL

Making your world a quieter place

CDM 60th Anniversary

CDM-QTRACK-JIG 3rd Rail Installation Catenaryless Power Supply System Napoli 2010

BOTYM 2011 - Brussels

Vincent Brasseur

Phase I – MOCKUP Installation

ASTS challenges CDM

cdm

Making your world a quieter place

- Ansaldo Signalling and Transportation Solution:
  - Headquartered in Genoa, Italy
  - Employs over 4,300 people in 28 different countries
  - 2009 revenues € 1.176 M
    - Gross operating margin of € 125 M
    - Net profits of € 88 M

Phase I – MOCKUP Installation

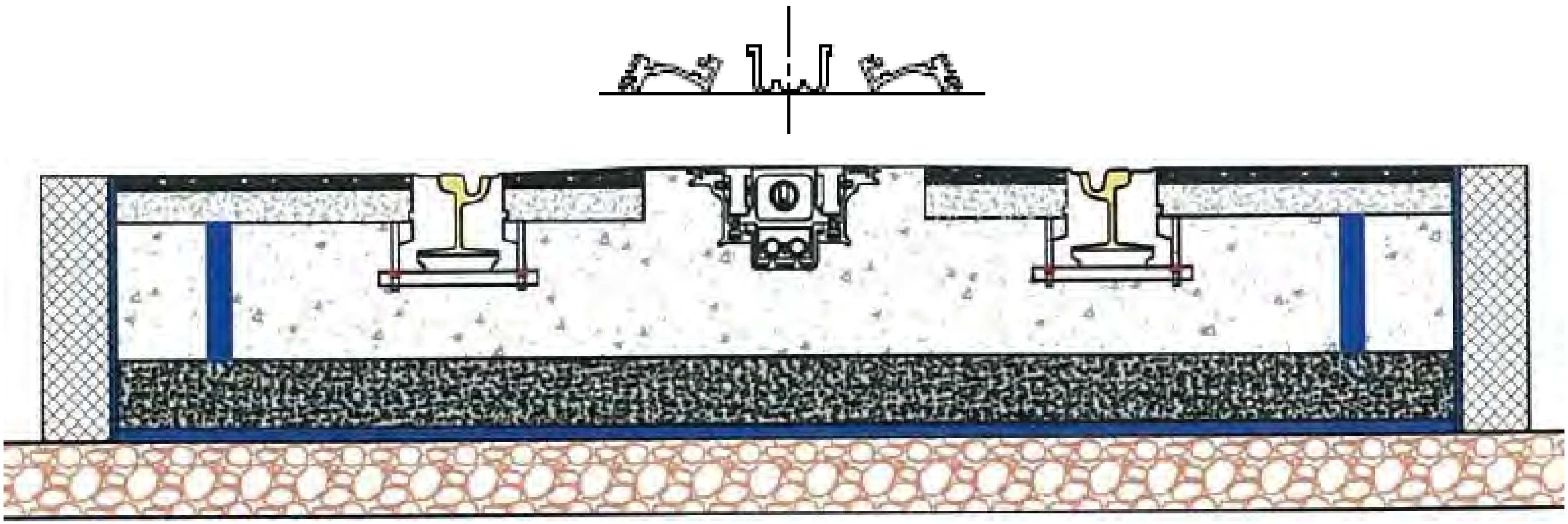
ASTS challenges CDM

- ASTS:
  - Leading technology company:
    - Listed on the Milan stock exchange
    - Operating in the global Railway & Mass Transit Transportation Systems business
    - Provision of:
      - Track Project Management
      - Catenaryless Power Supply & Signalling Systems and Services
      - Traffic Management
      - Planning
      - Train Control
    - Acts as lead contractor and turnkey provider on major projects worldwide (Europe, Middle-East, Asia, …)

Phase I – MOCKUP Installation

ASTS challenges CDM

- ASTS challenges CDM to prove:
  - We can efficiently install a 36 lmst MOCKUP included:
    - CDM-QTRACK-JIG-60R2-HP-R system into CDM-FSM-L10 floating slab track:
    - ASTS Ground Power Supply System Packing – called “**Trogolo**”:3 pieces



Phase I – MOCKUP Installation

ASTS challenges CDM

Making your world a quieter place

- ASTS Catenaryless Power Supply System = Tramwave: 2 elements:
  - Ground Power Supply System packed in the « Trogolo »
  - Tramway Vehicle Magnetic Power Collector = 3 main functions:
    - Activation of +- 2m line segments
    - Current pick up & Current return
    - Guide the Vehicle Magnetic Power Collector over the line

Phase I – MOCKUP Installation

CDM: “Yes we can”!

cdm

Making your world a quieter place

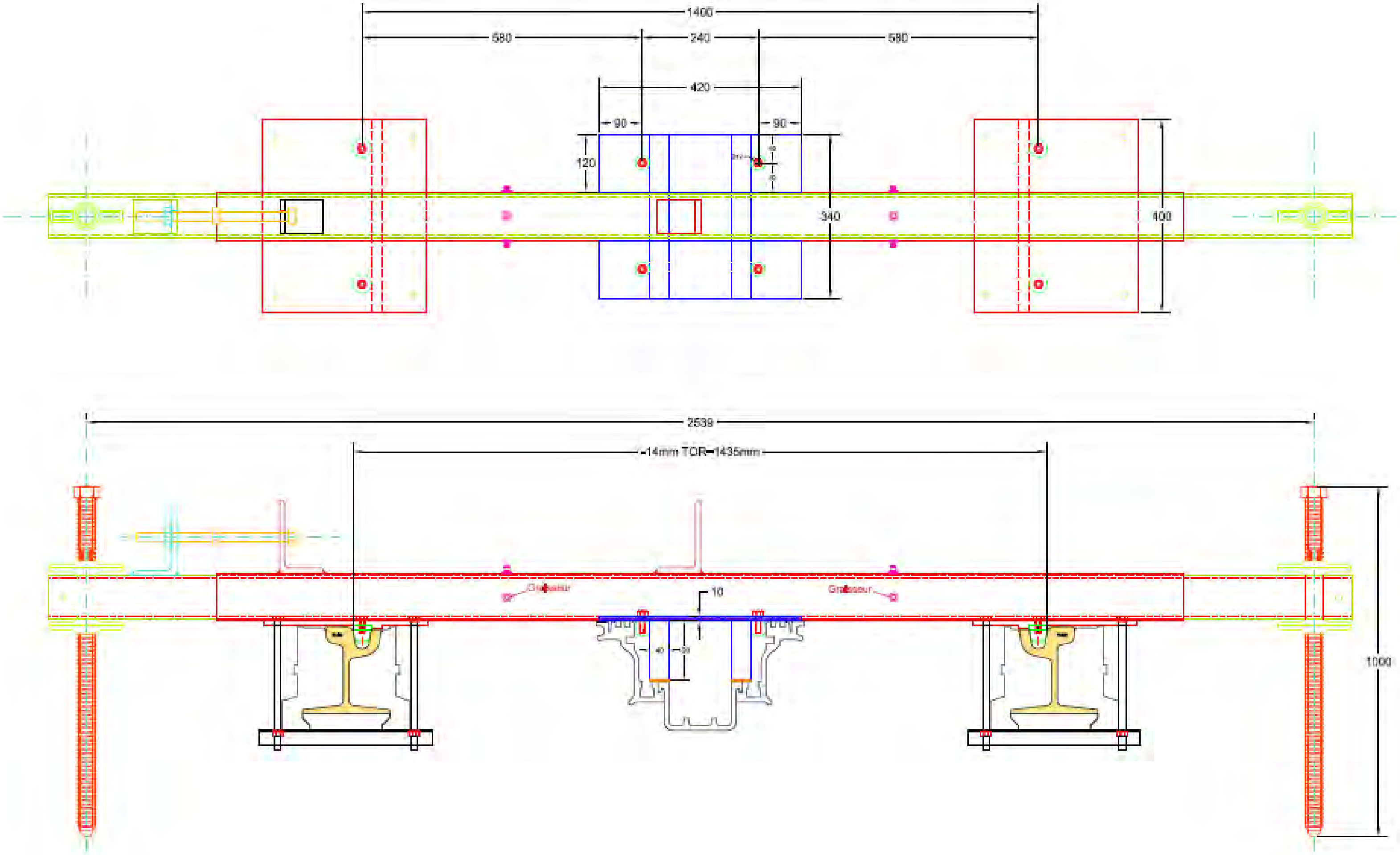
- CDM’s reply: « Yes we can »!
  - CDM supplies asap:
    - **36 lmst** CDM-QTRACK-JIG-60R2-HP-R profiles
    - **# 6** CDM-JIG-TRAMWAVE
    - **100 m^2** CDM-FSM-L10 horizontal mats floating slab track
    - **50 m^2** CDM-FSM-L10 vertical mats floating slab track

Phase I – MOCKUP Installation

CDM: “Yes we can”!

Making your world a quieter place

- New CDM-JIG design for Mockup:

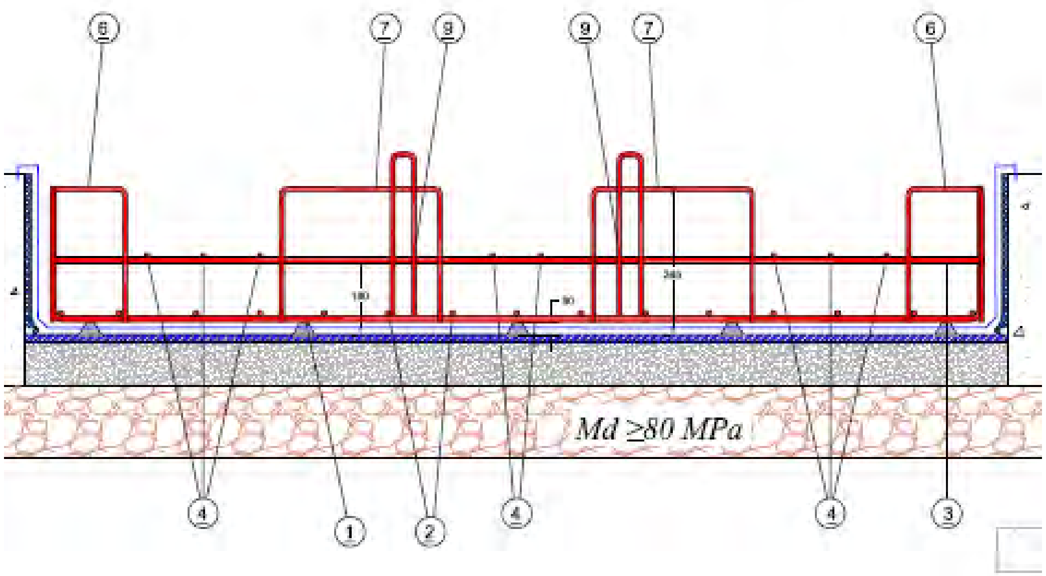


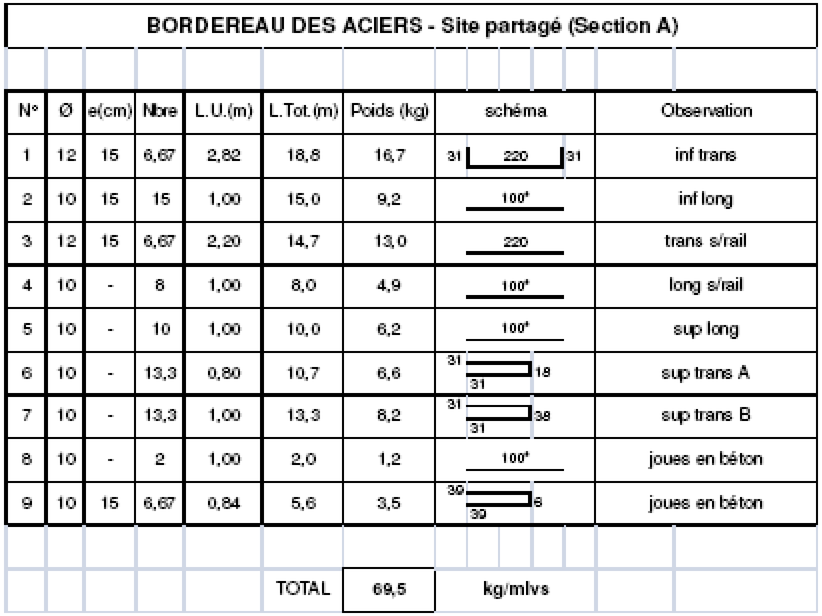
Phase I – MOCKUP Installation

CDM: “Yes we can”!

Making your world a quieter place

Mechanical Calculation Note:





BORDEREAU DES ACIERS - Site partagé (Section A)

N°	Ø	e(cm)	Nbre	L.U.(m)	L.Tot.(m)	Poids (kg)	schéma	Observation
1	12	15	6,67	2,82	18,8	16,7	31 220 31	inf trans
2	10	15	15	1,00	15,0	9,2	100*	inf long
3	12	15	6,67	2,20	14,7	13,0	220	trans s/rail
4	10	-	8	1,00	8,0	4,9	100*	long s/rail
5	10	-	10	1,00	10,0	6,2	100*	sup long
6	10	-	13,3	0,80	10,7	6,6	31 18 31	sup trans A
7	10	-	13,3	1,00	13,3	8,2	31 38 31	sup trans B
8	10	-	2	1,00	2,0	1,2	100*	joues en béton
9	10	15	6,67	0,84	5,6	3,5	39 6 39	joues en béton
					TOTAL	69,5	kg/mlvs	

Phase I – MOCKUP Installation

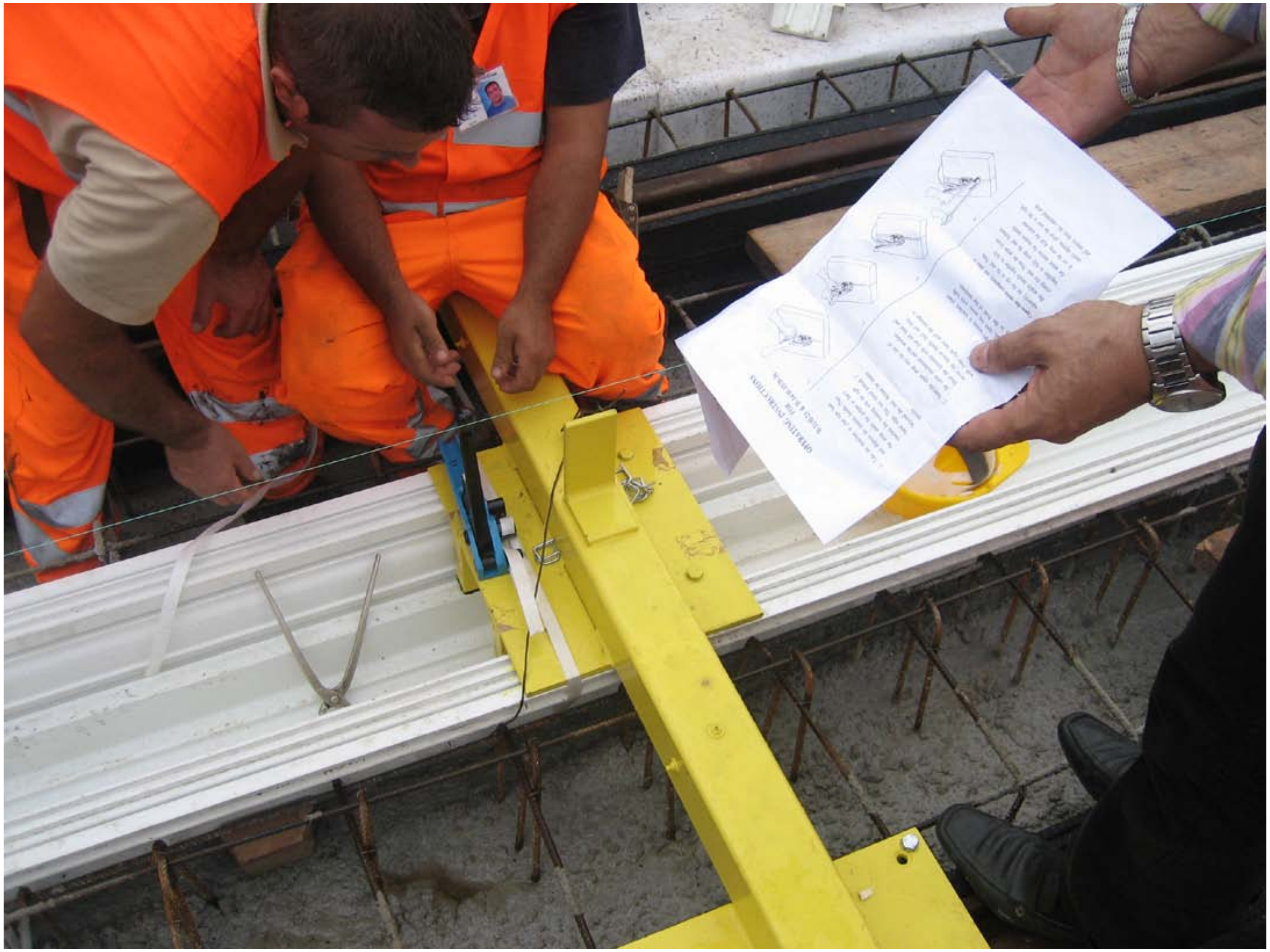
ASTS'site Mockup Installation

Making your world a quieter place

Phase I – MOCKUP Installation

ASTS'site Mockup Installation

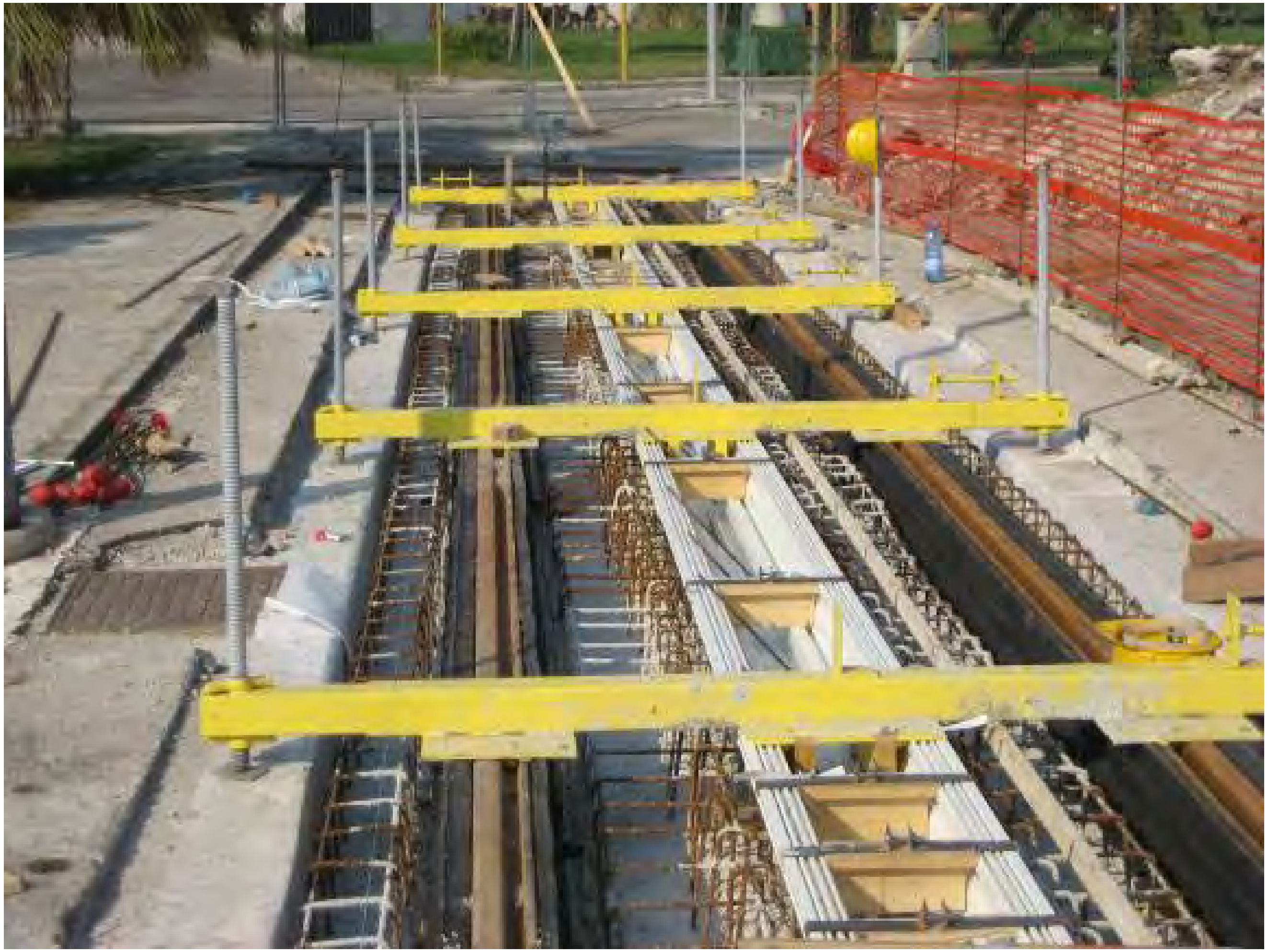
Making your world a quieter place



Phase I – MOCKUP Installation

ASTS'site Mockup Installation

Making your world a quieter place



Phase I – MOCKUP Installation

ASTS'site Mockup Installation

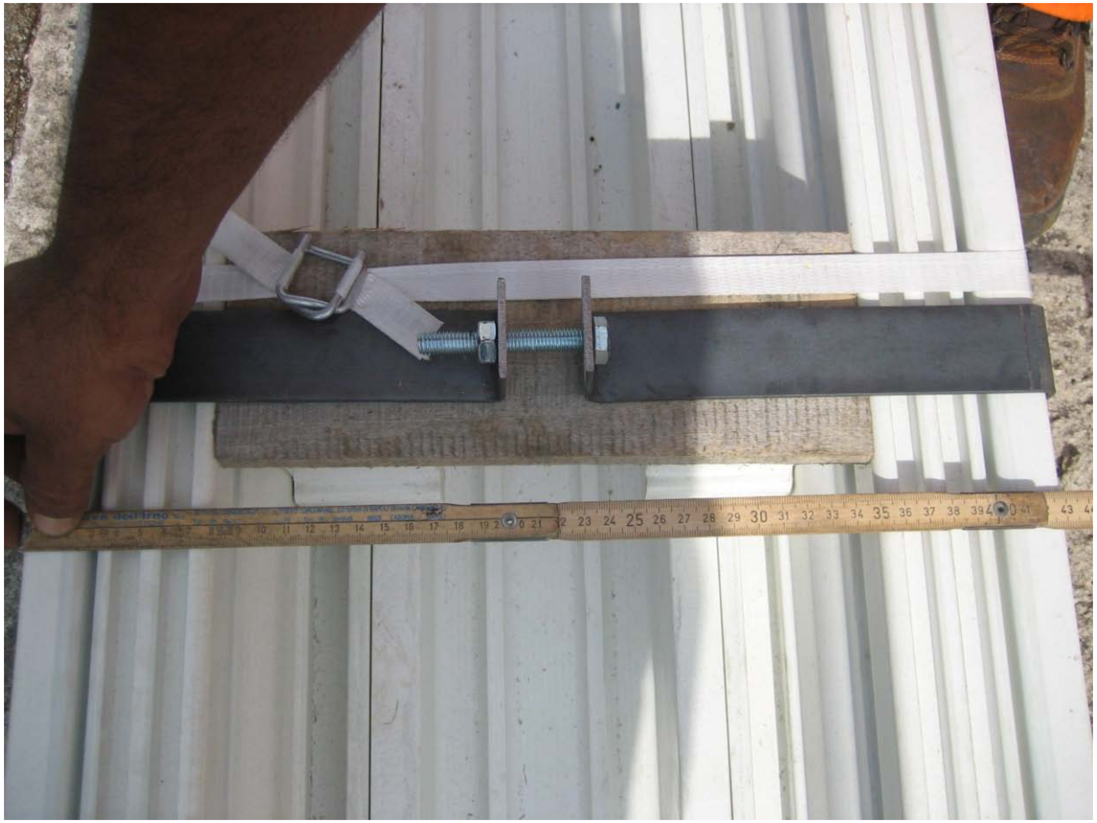
Making your world a quieter place

Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- ASTS: « OK we trust you, just do it on site in Napoli now»
- « But please first improve the plastic straps system you used to fix the trogolo because we need better results in final positionning »

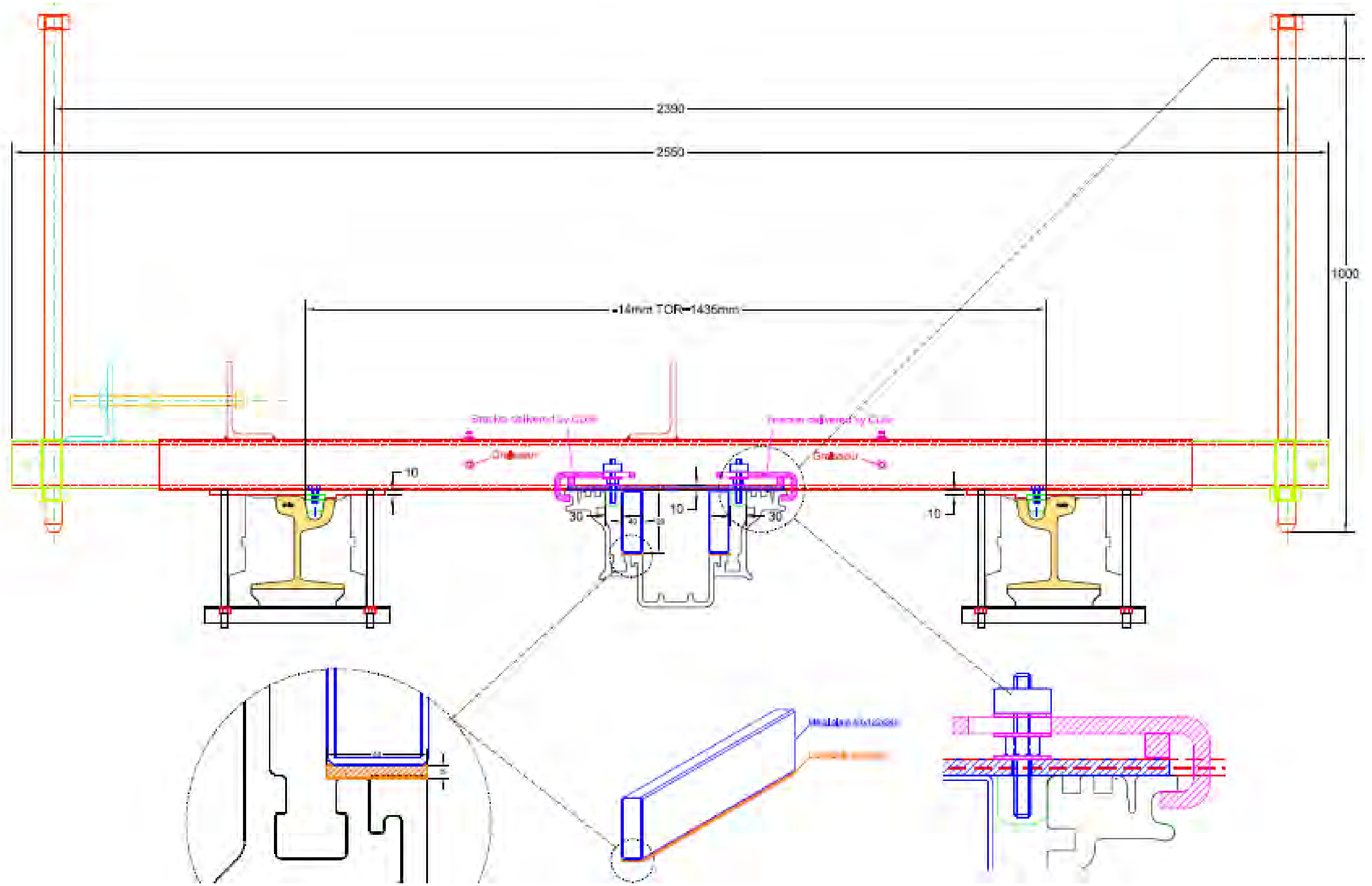


Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- CDM-JIG's design improvement: 4 Brackets:

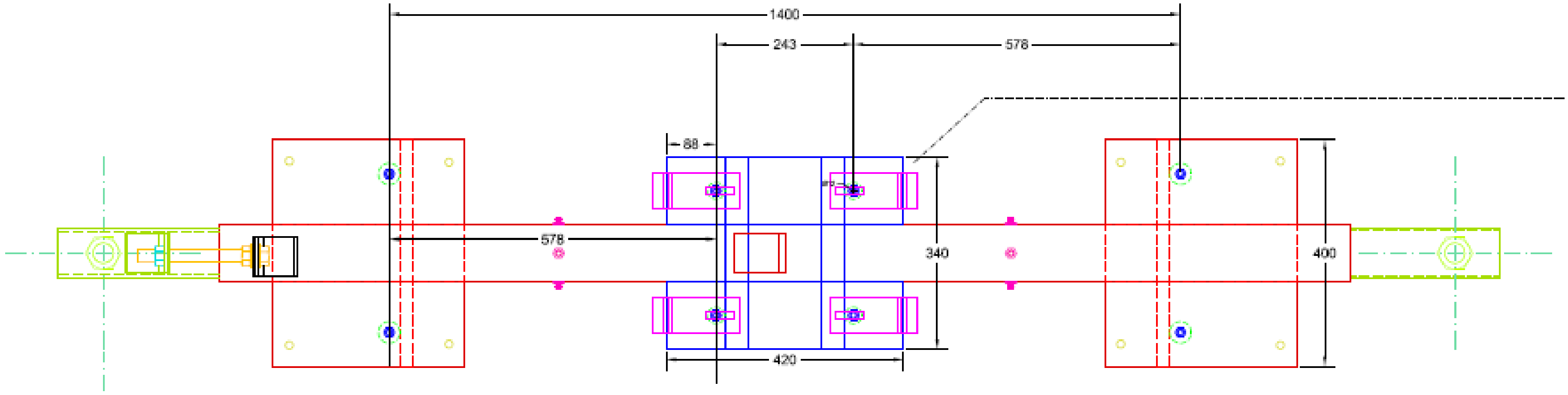


Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- CDM-JIG's design improvement: 4 Brackets:

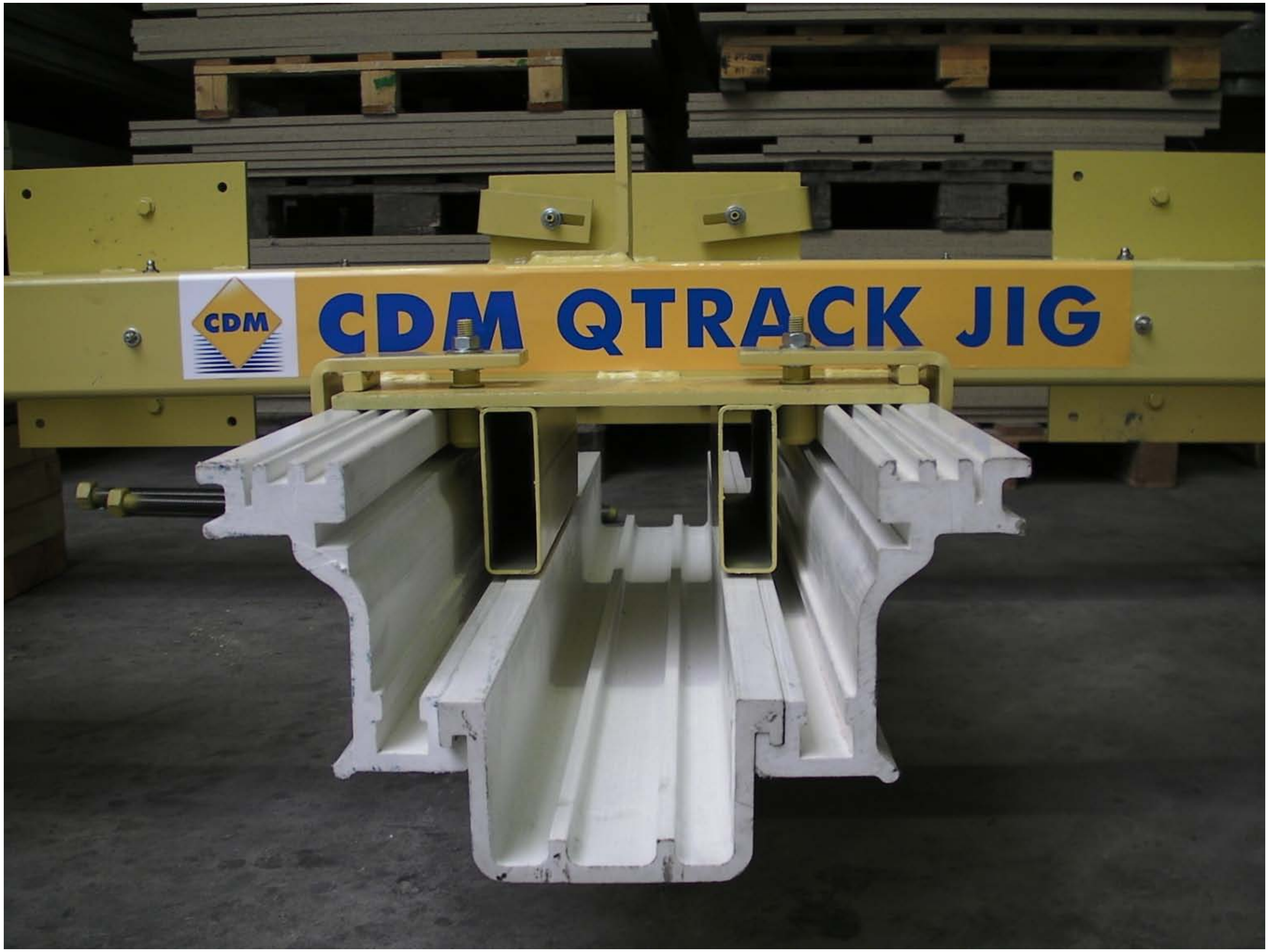


Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- CDM-JIG’s improvement: 4 Brackets: test in factory:

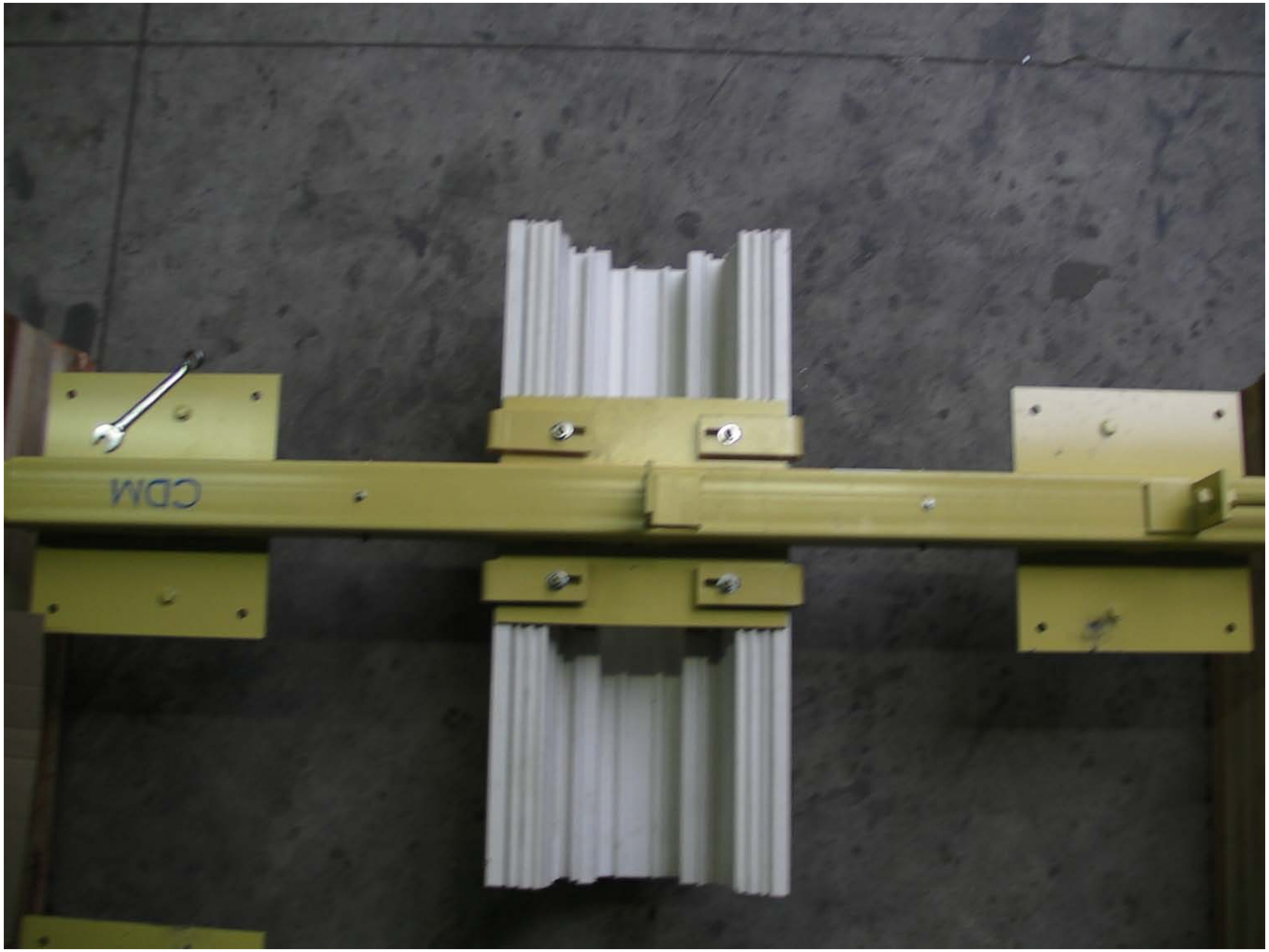


Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- CDM-JIG's improvement: 4 Brackets: test in factory:



Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

- CDM-JIG's improvement: 4 Brackets: test in factory:

Phase I – MOCKUP Installation

Phase I - Conclusion

Making your world a quieter place

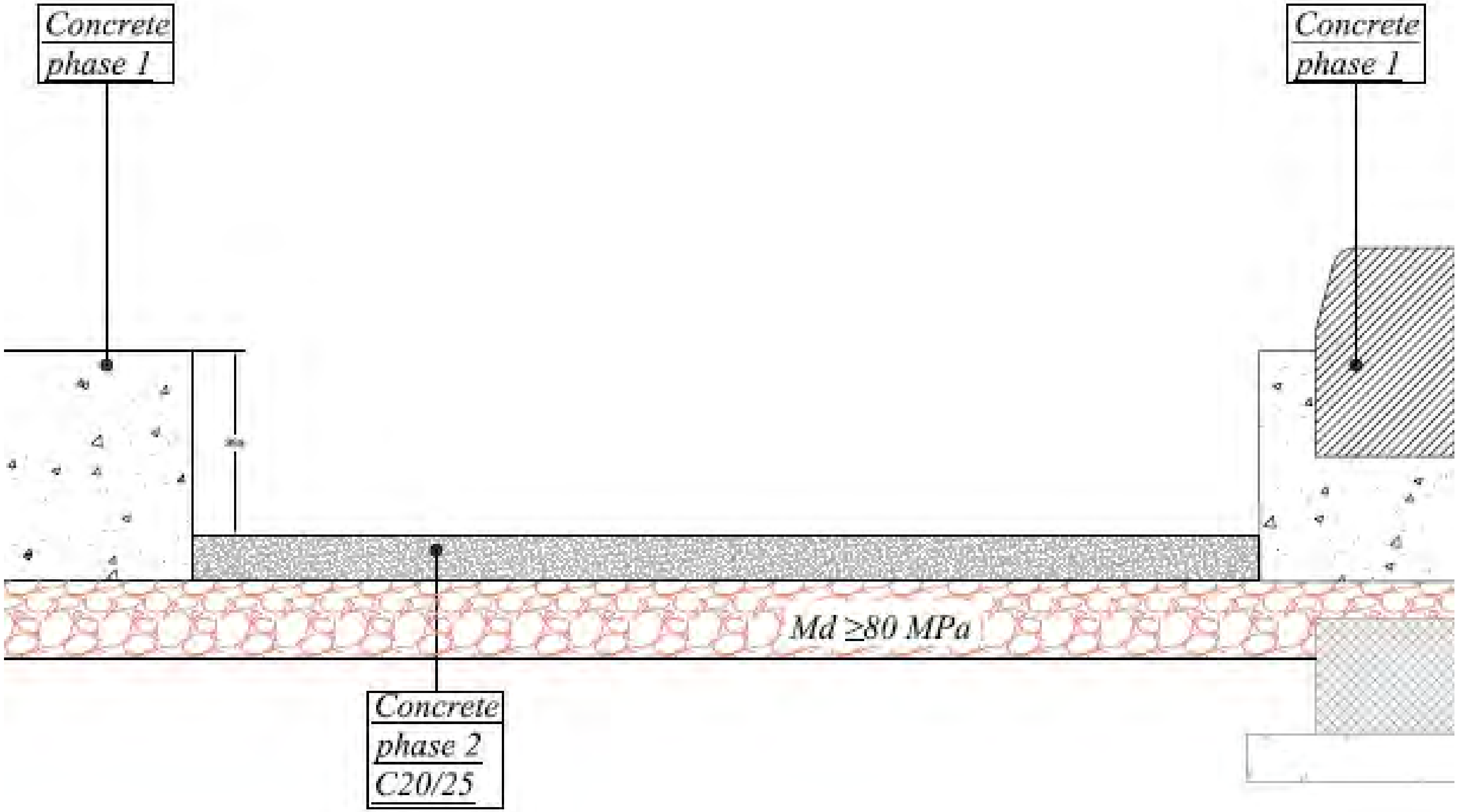
- ASTS: « OK you did it, we order for a first installation in Via Stadera, Napoli:
  - **600 lmst** CDM-QTRACK-JIG-60R2-HP-R profiles
  - **# 30** CDM-JIG-TRAMWAVE
  - **1500 m^2** CDM-FSM-L10 horizontal mats floating slab track
  - **500 m^2** CDM-FSM-L10 vertical mats floating slab track

Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

Excavation and Lean Concrete phase 2:

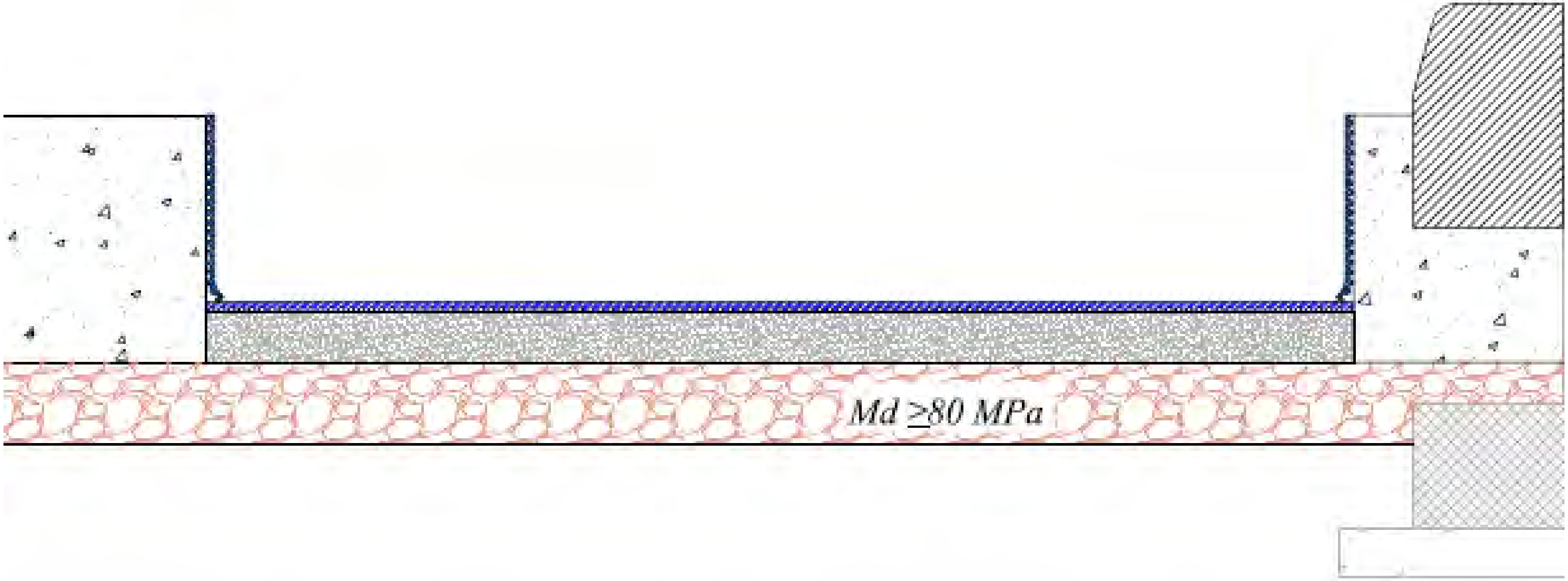


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Horizontal & Vertical CDM-FSM Installation:



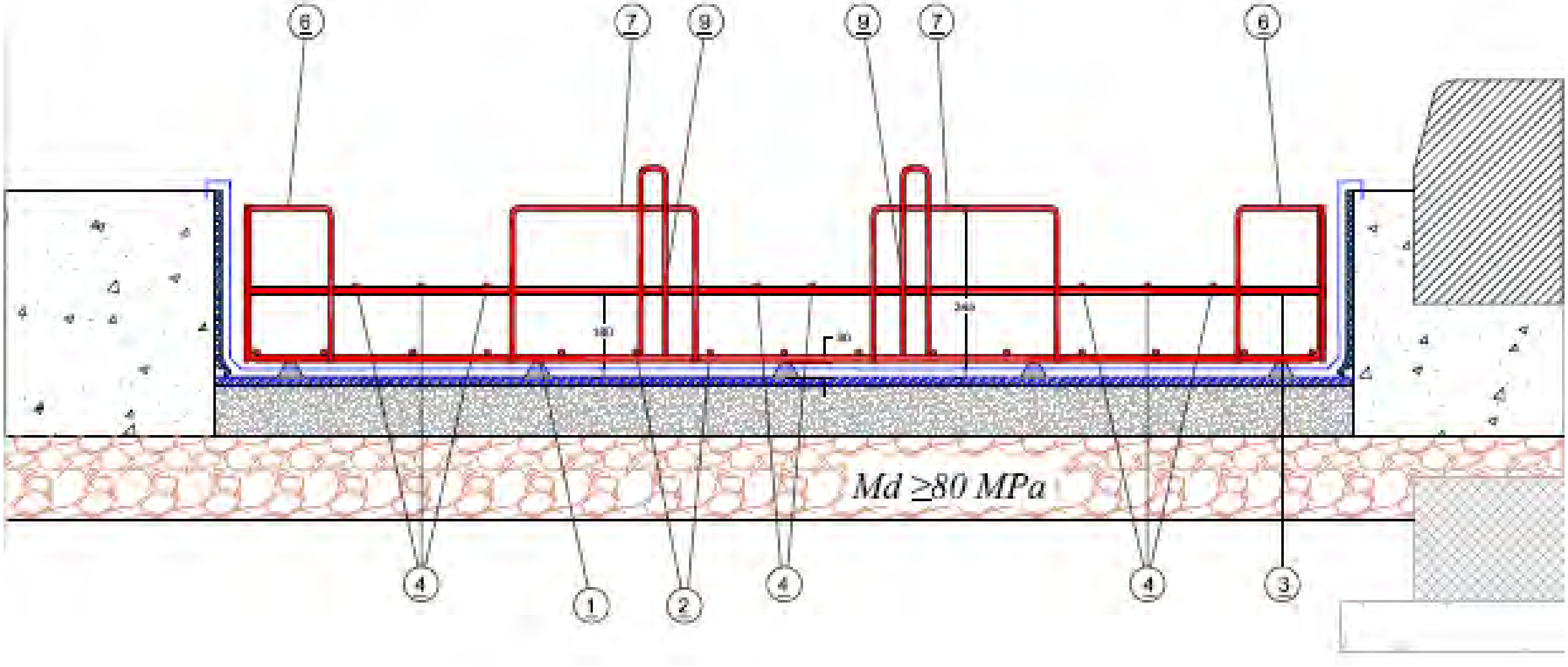
Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

cdm

Making your world a quieter place

- Steel Reinforcements further to Mechanical Calculation Note:

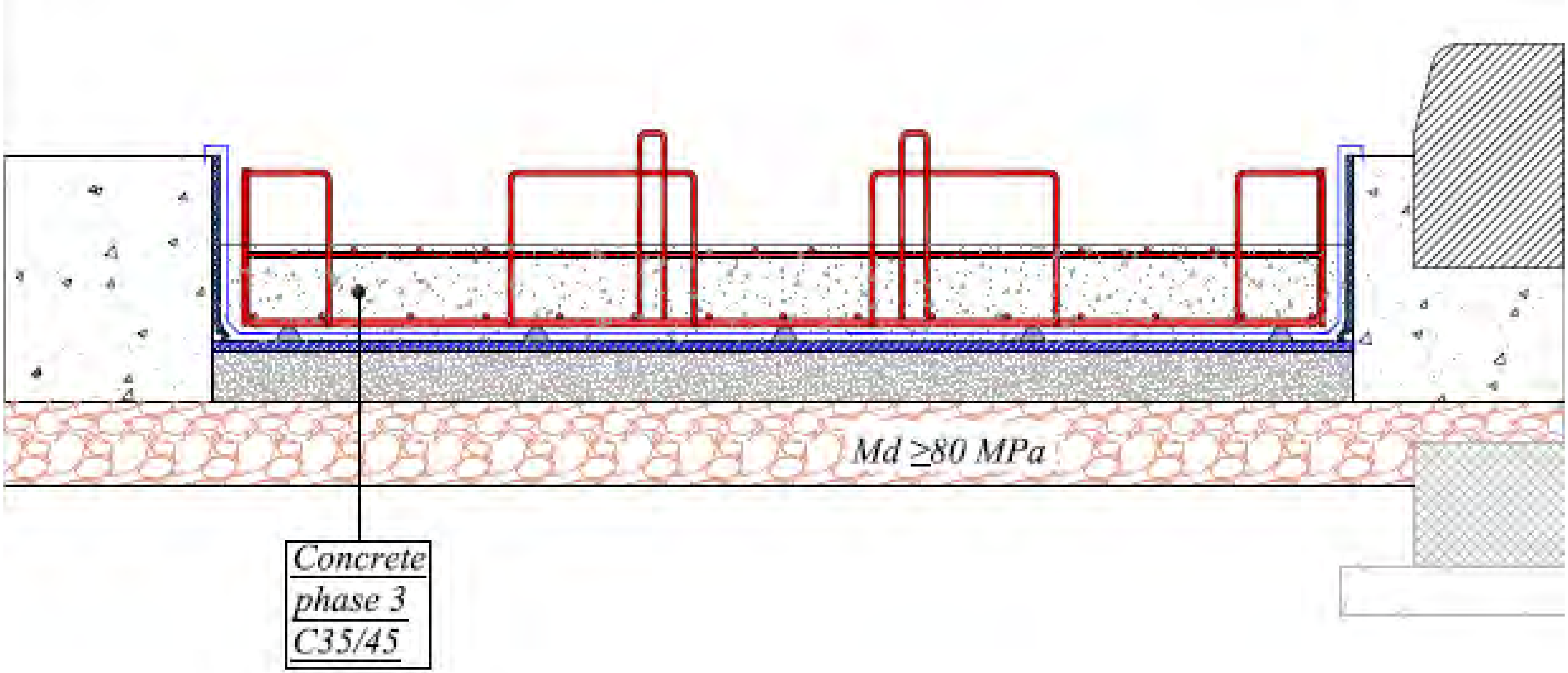


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Concrete phase 3:

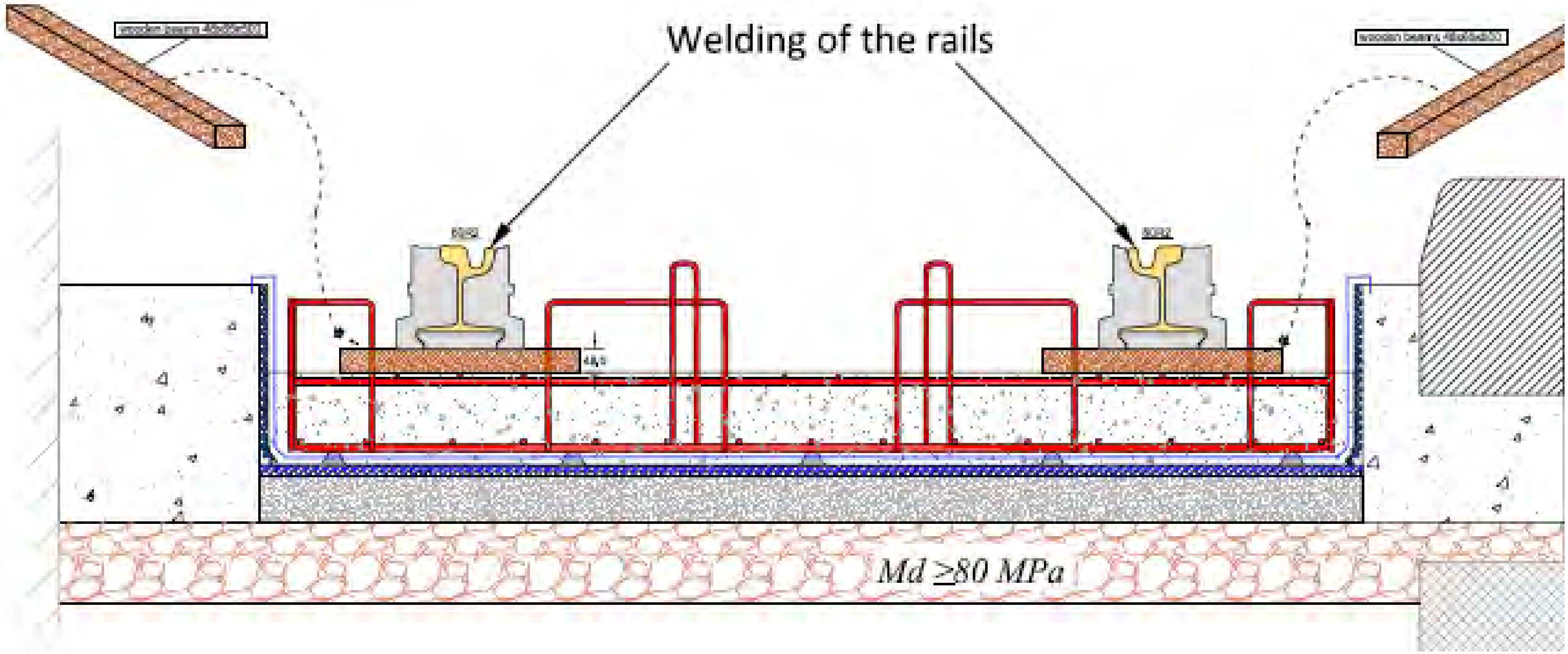


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Encapsulated rails posed on temporary wood sleepers
- Rails welding :

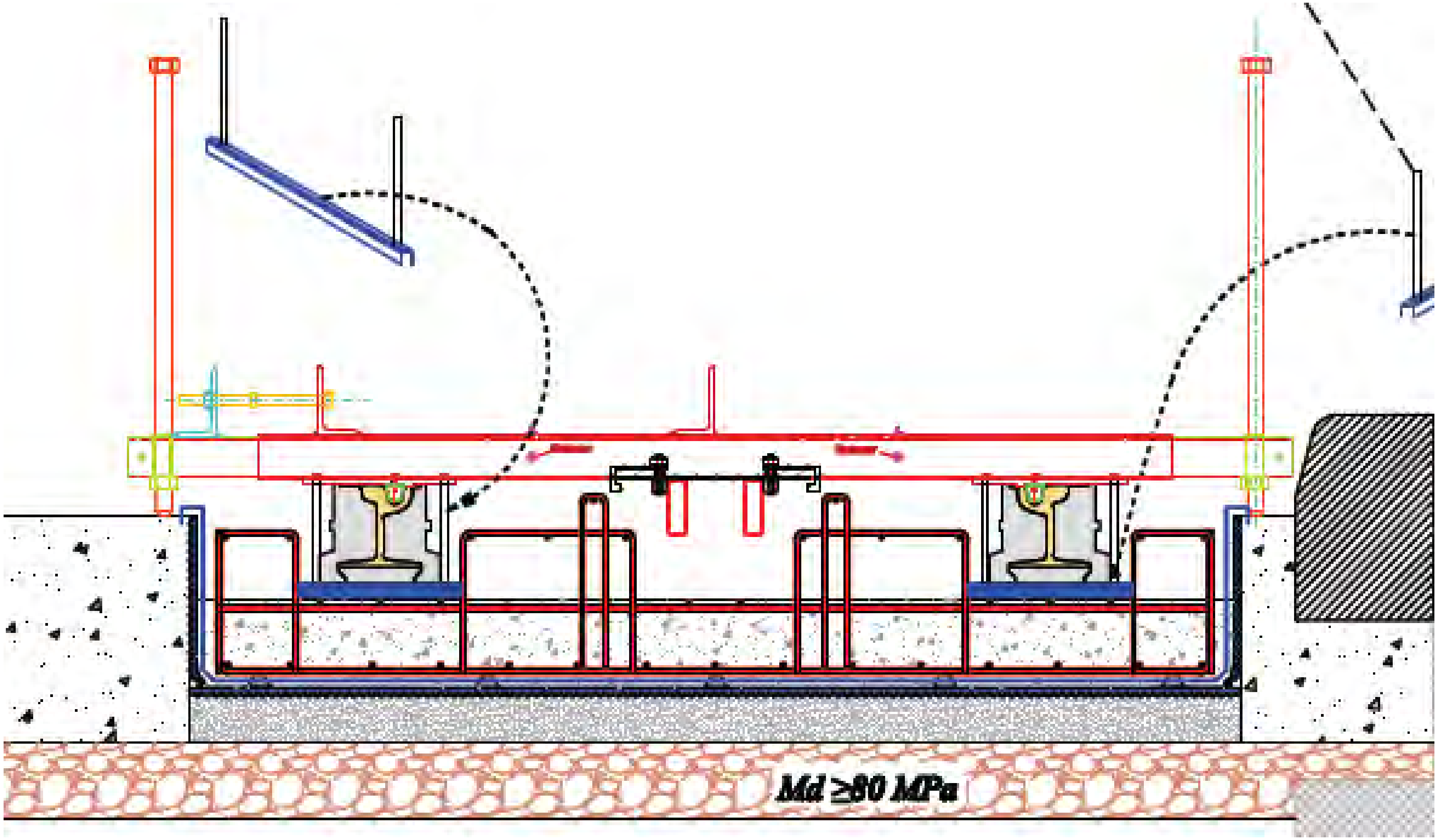


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Track Levelling in X, Y, Z using CDM-JIG's:

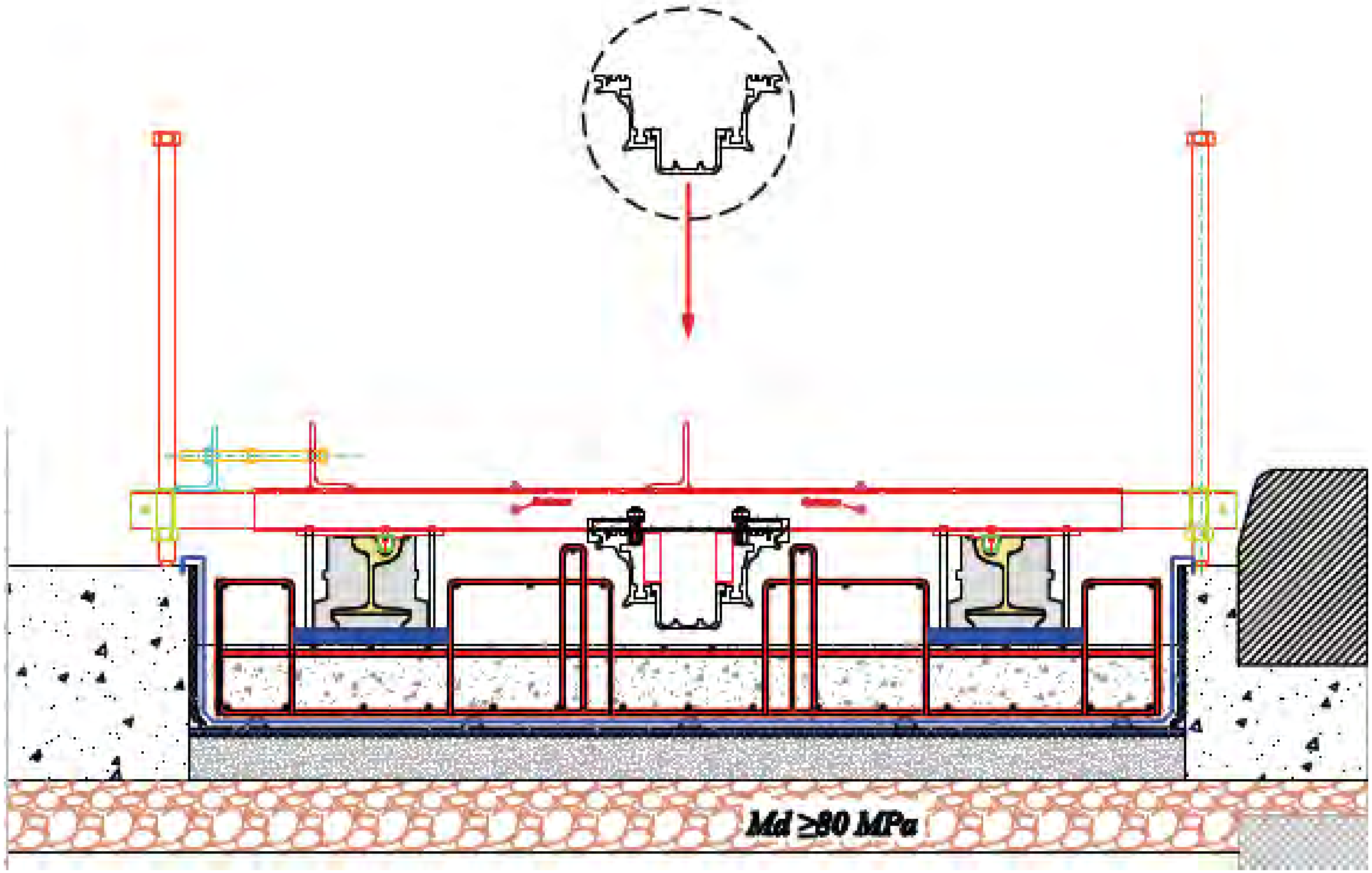


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Trogolo installation using CDM-JIG’s + Brackets:

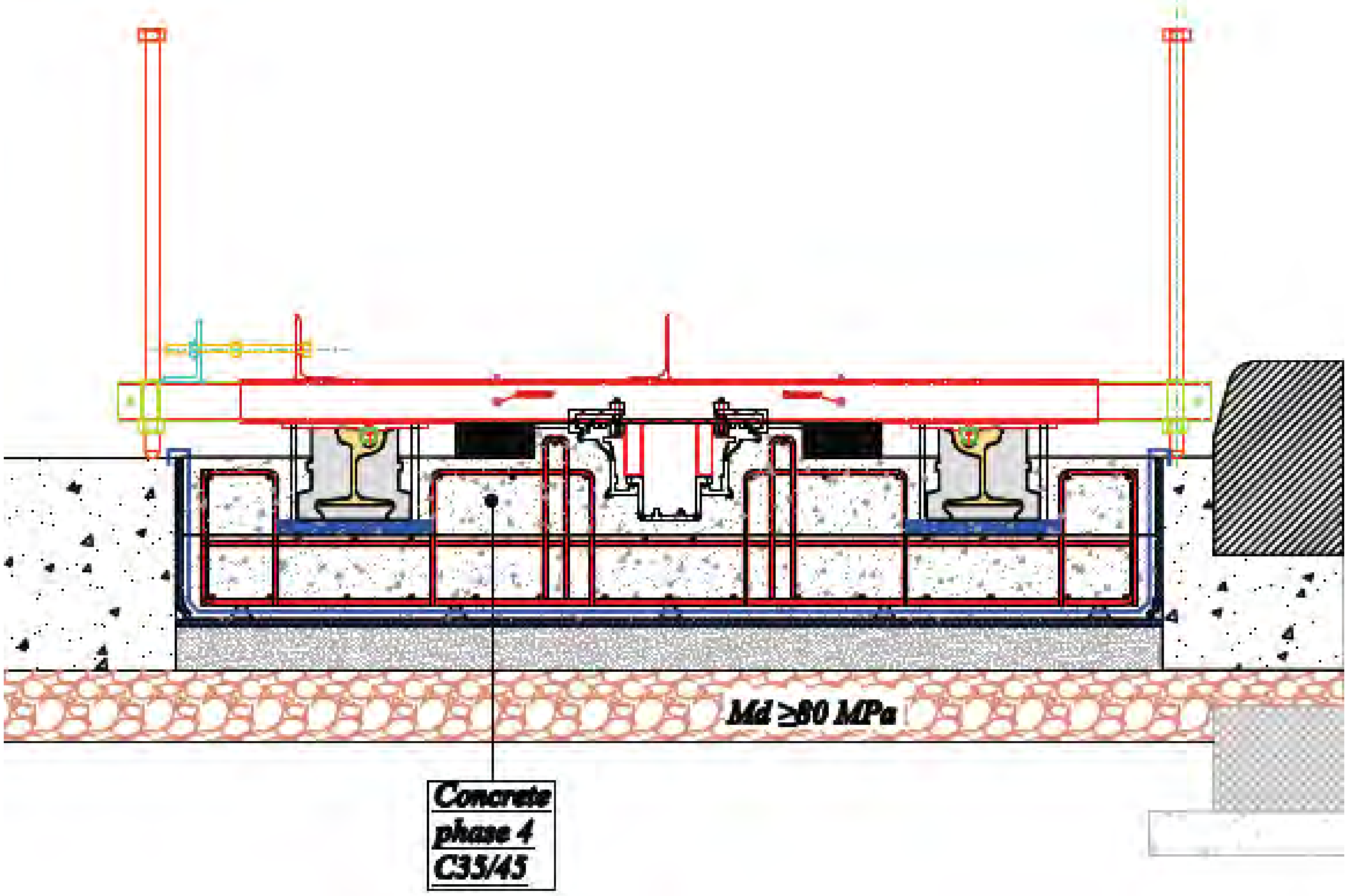


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

Concrete phase 4:

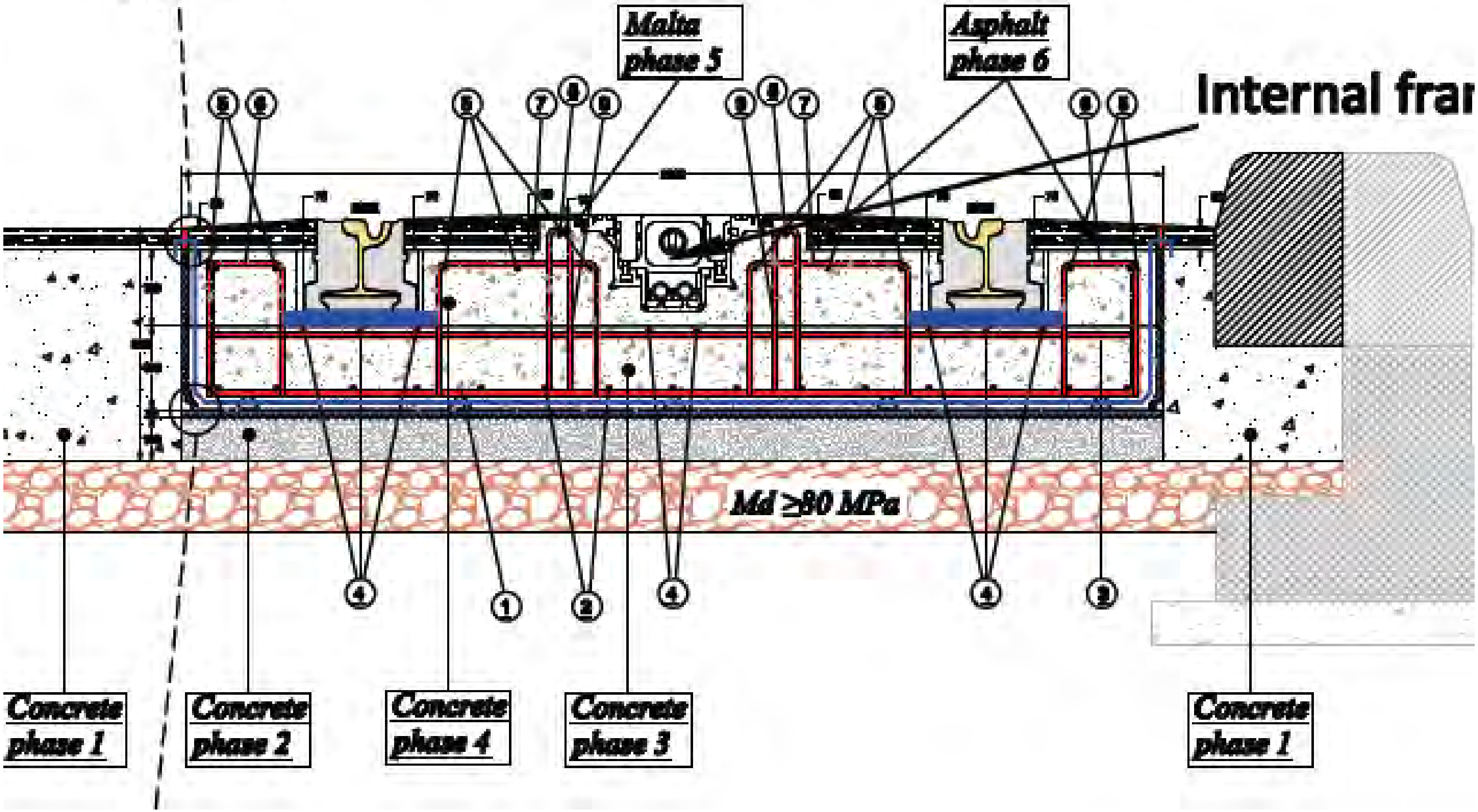


Phase II – Napoli Via Stadera Installation

Phase II – Installation Sequence - Mixed Traffic Zone

Making your world a quieter place

- Concrete phase 4 & Asphalt & Malta:



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation : CDM-profiles gluing

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Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: CDM-FSM

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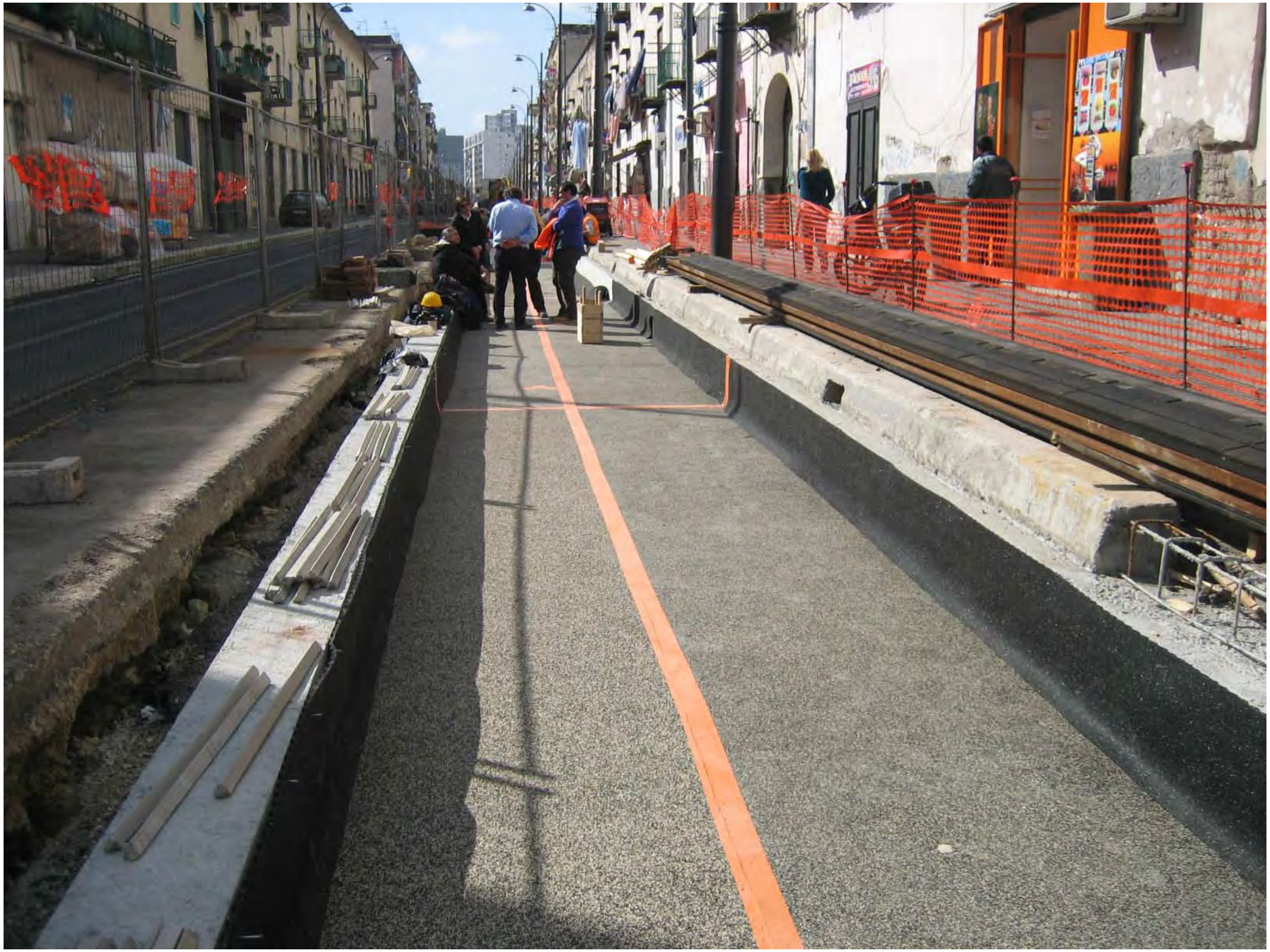

Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: steel reinforcements

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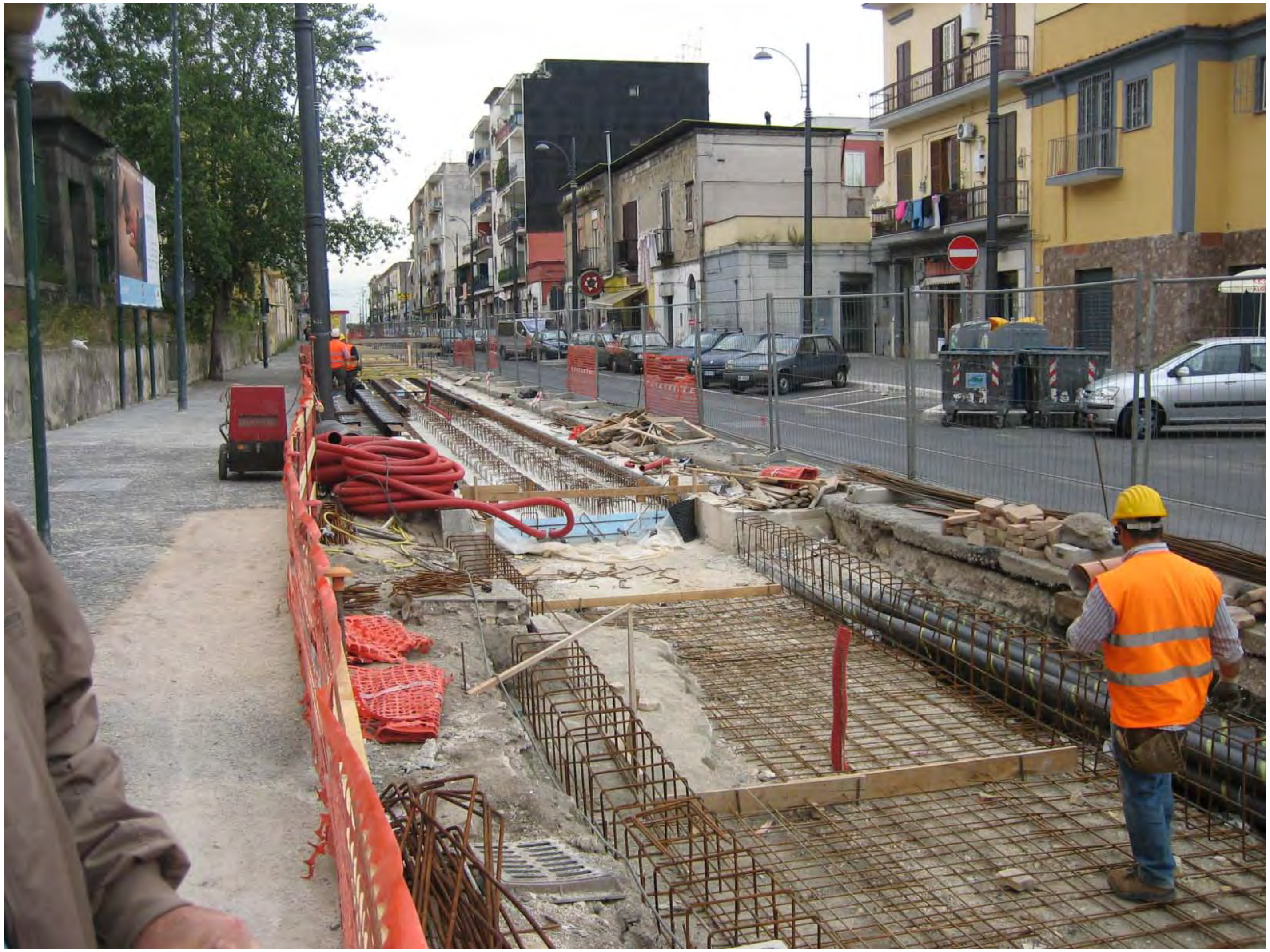

Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: CDM-JIG's

cdm

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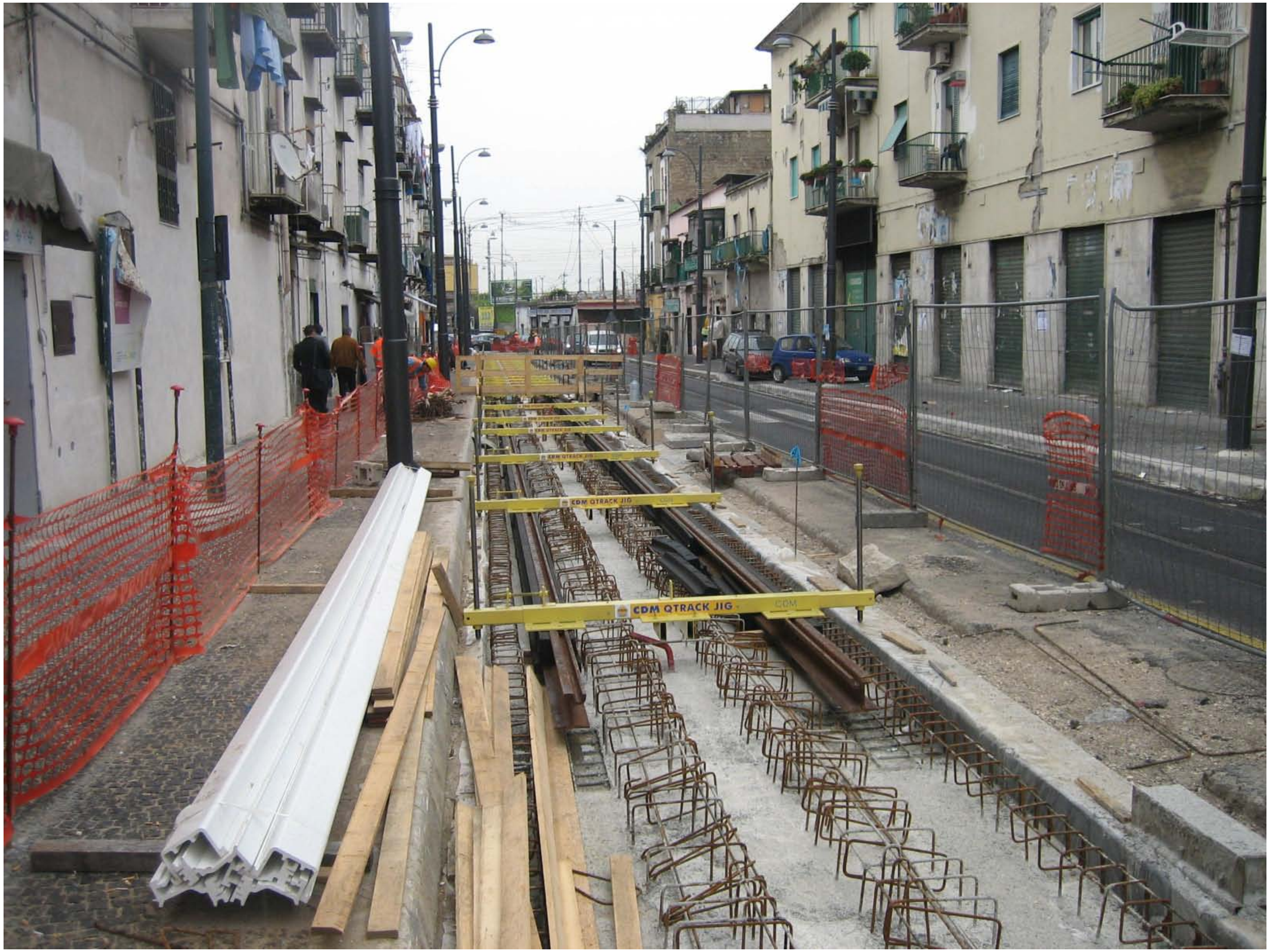
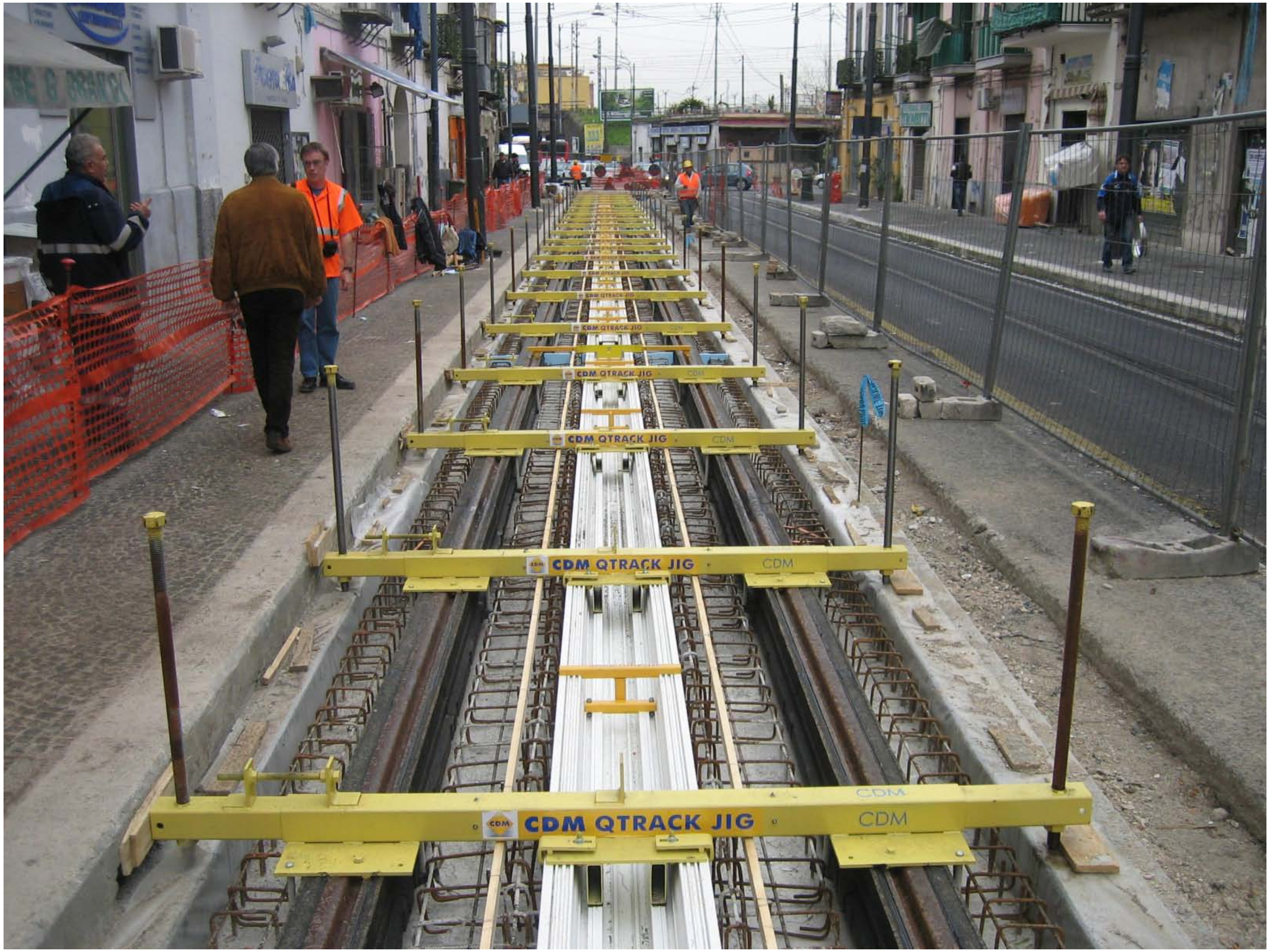


Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Trogolo

Making your world a quieter place



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Trogolo & Brackets

Making your world a quieter place

Phase II – Napoli Via Stadera Installation

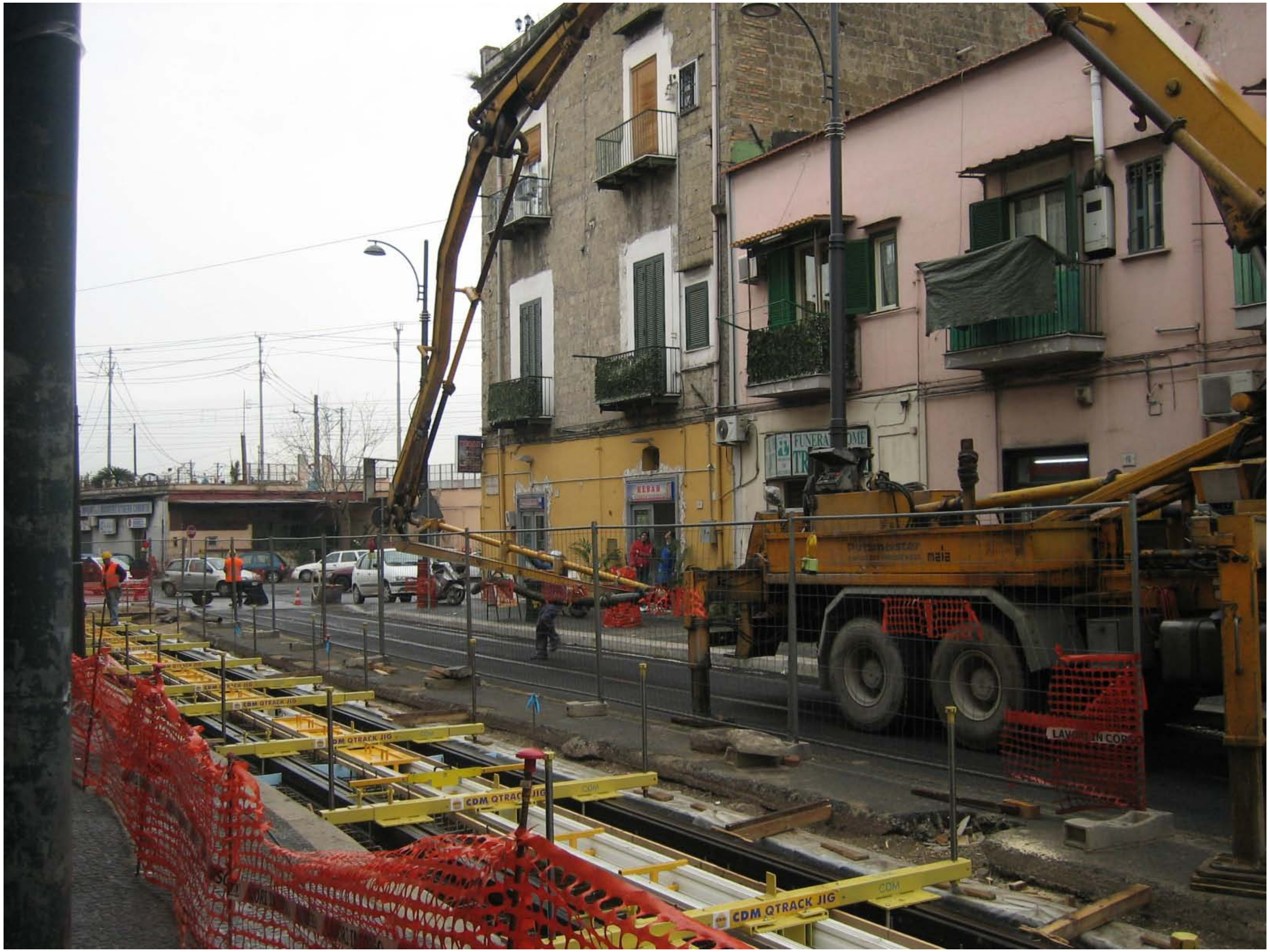
Phase II – On Site Installation: CDM-FSM

Making your world a quieter place

Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

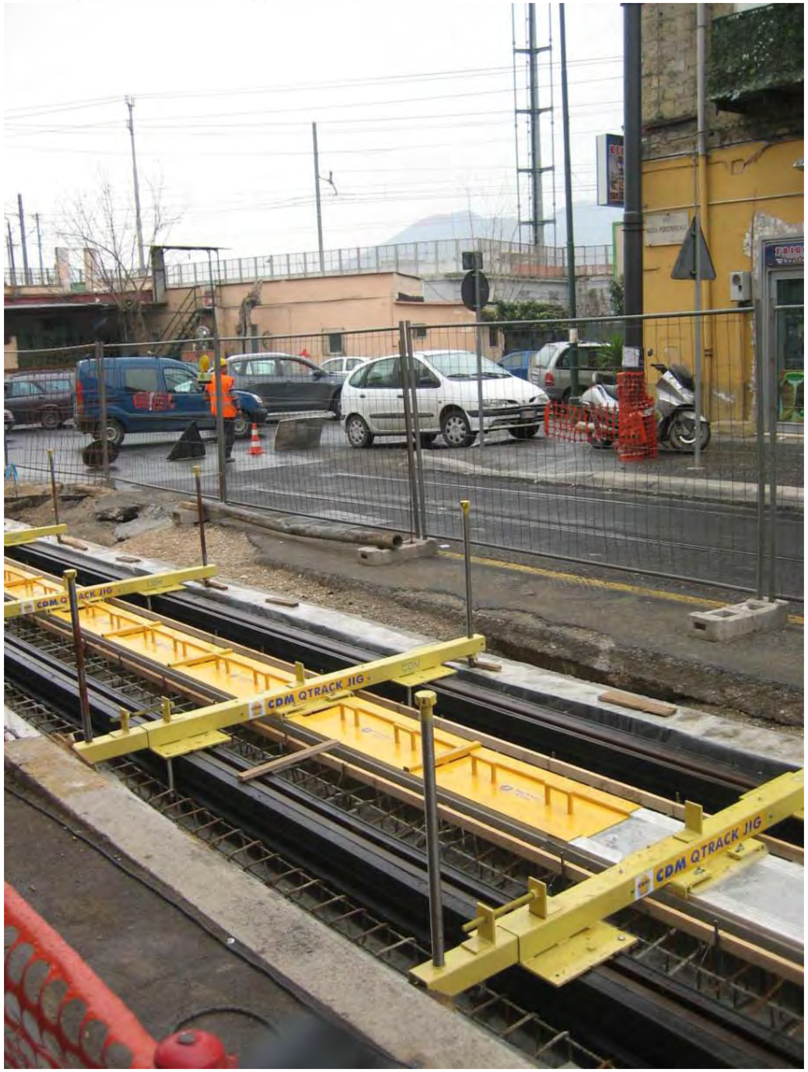
Making your world a quieter place

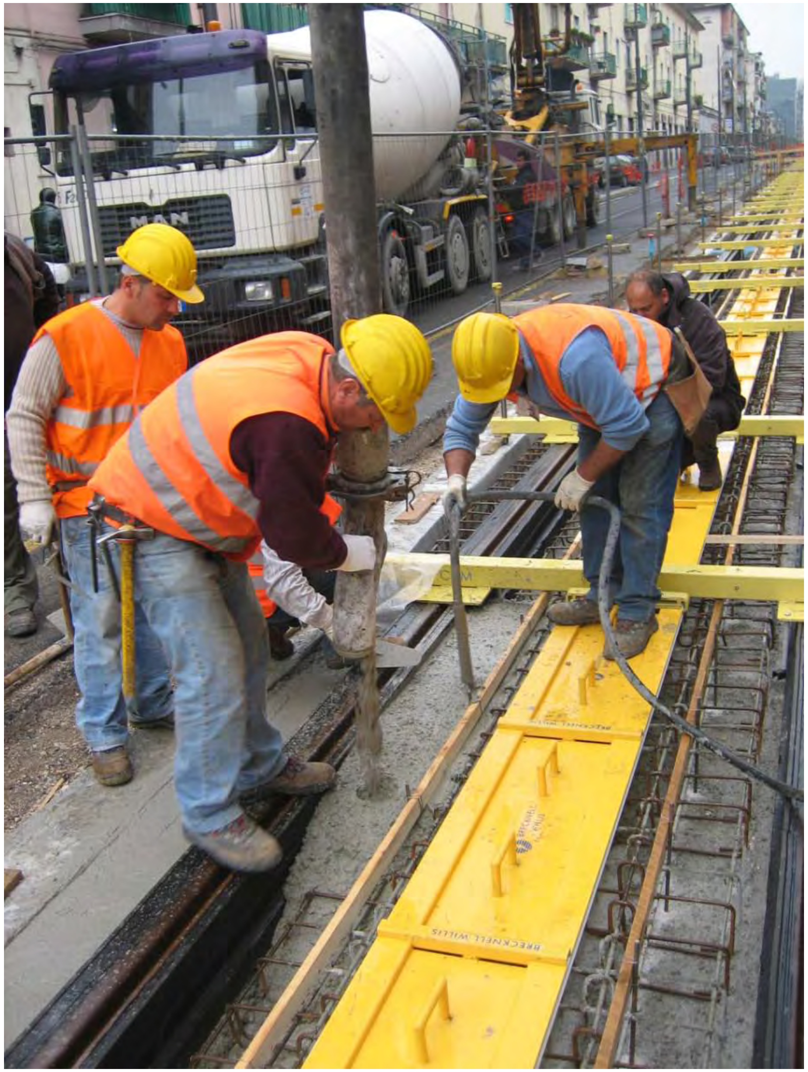


Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

Making your world a quieter place

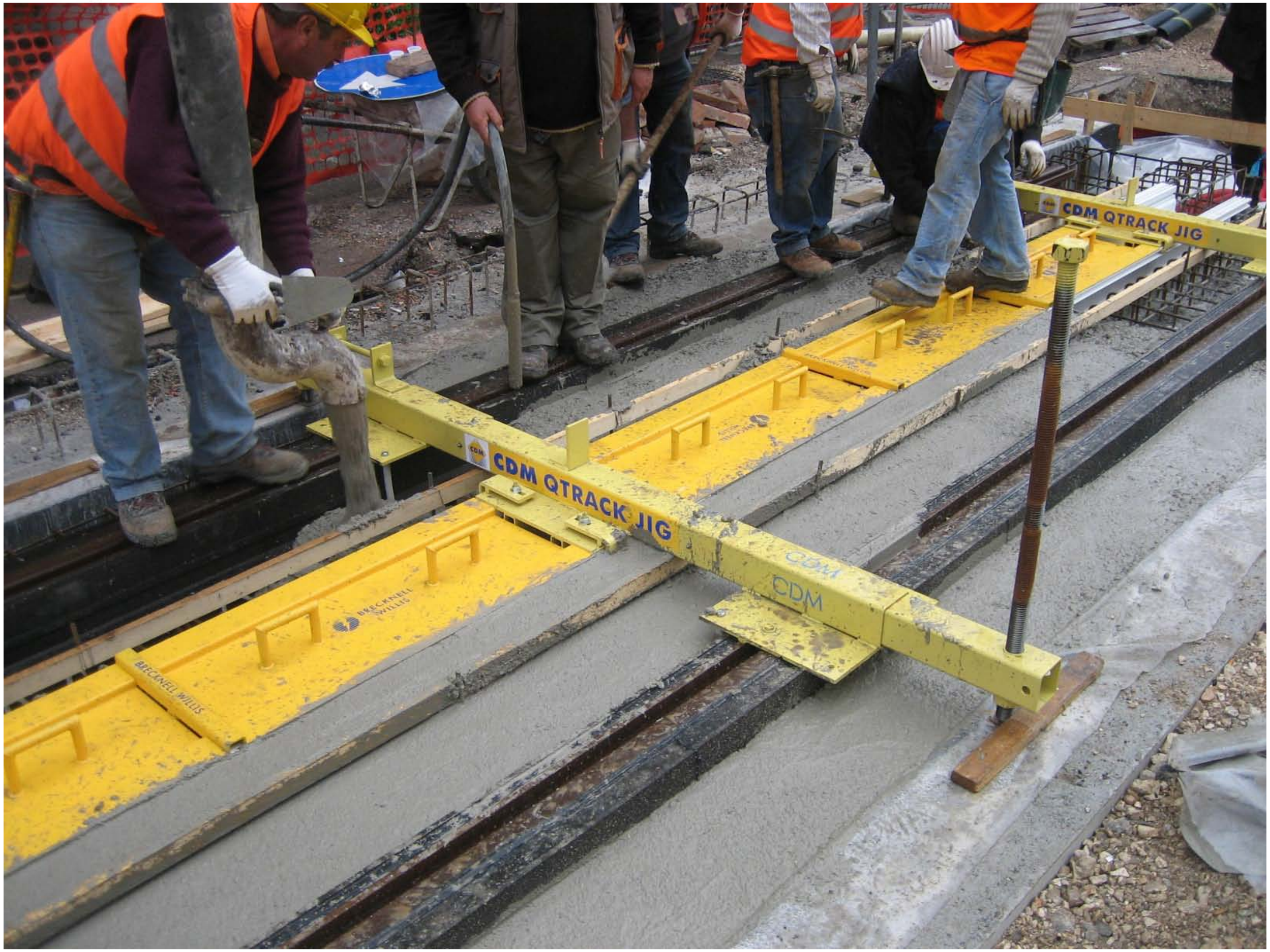




Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

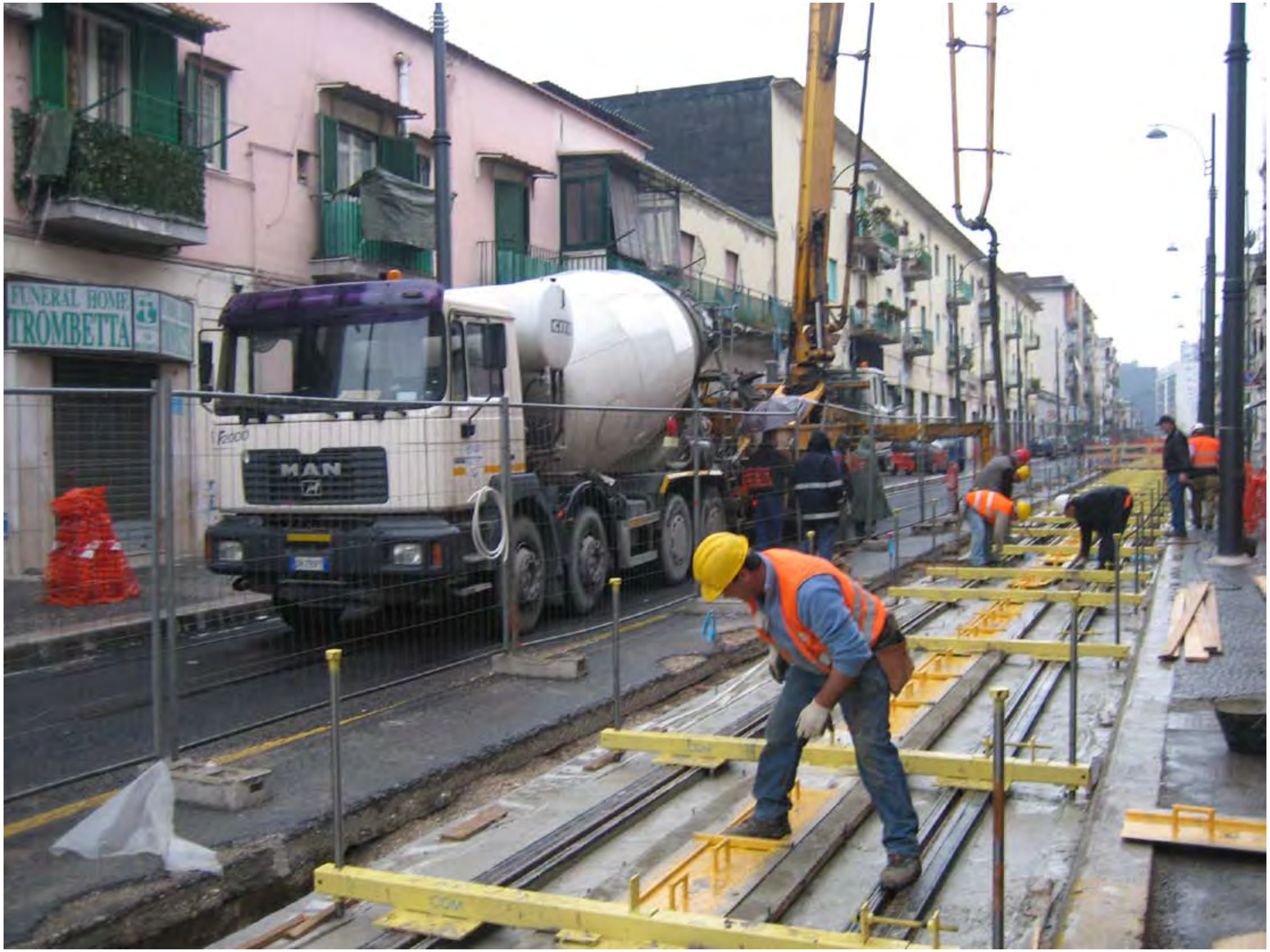
Making your world a quieter place



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

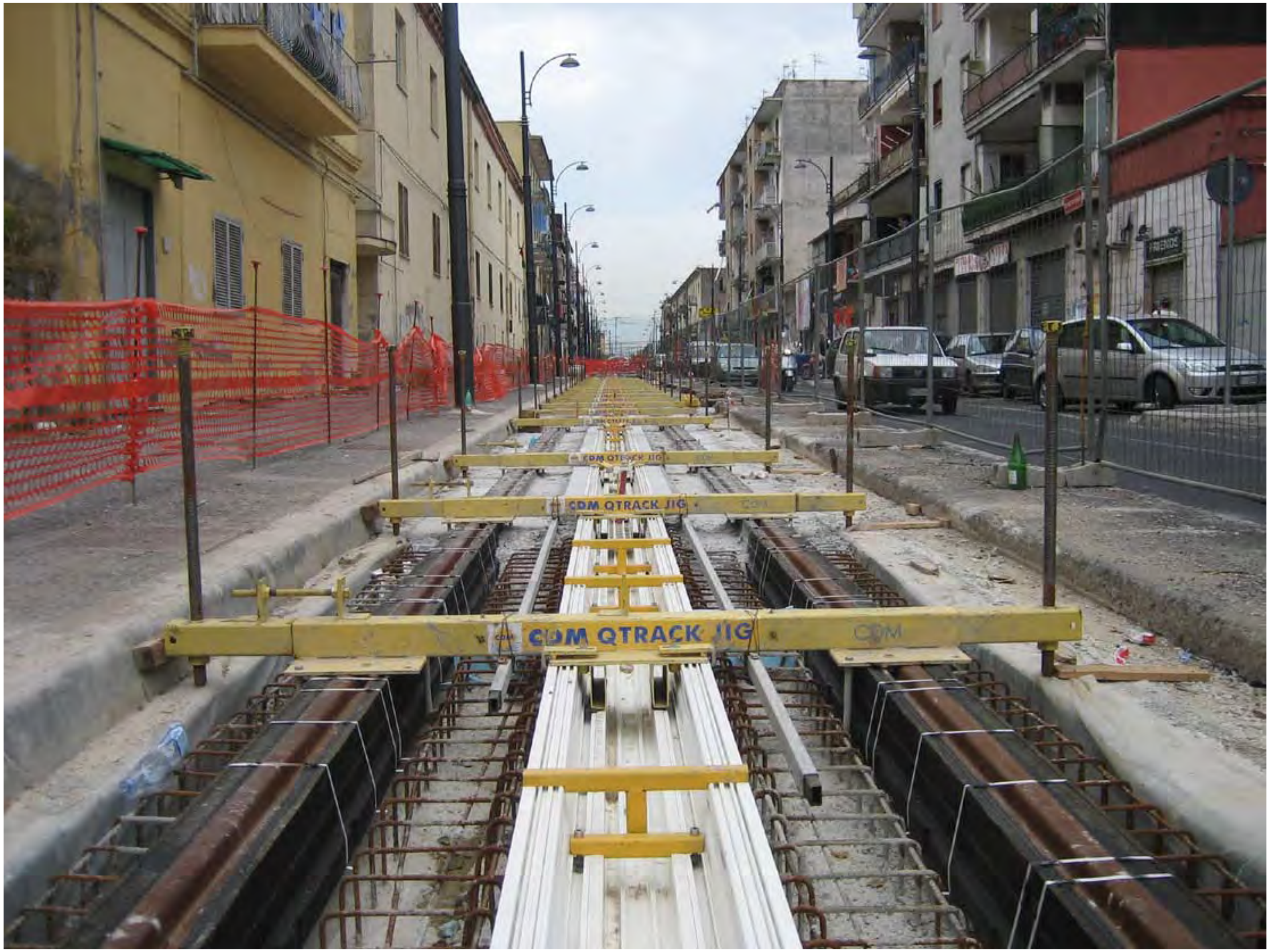
Making your world a quieter place



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

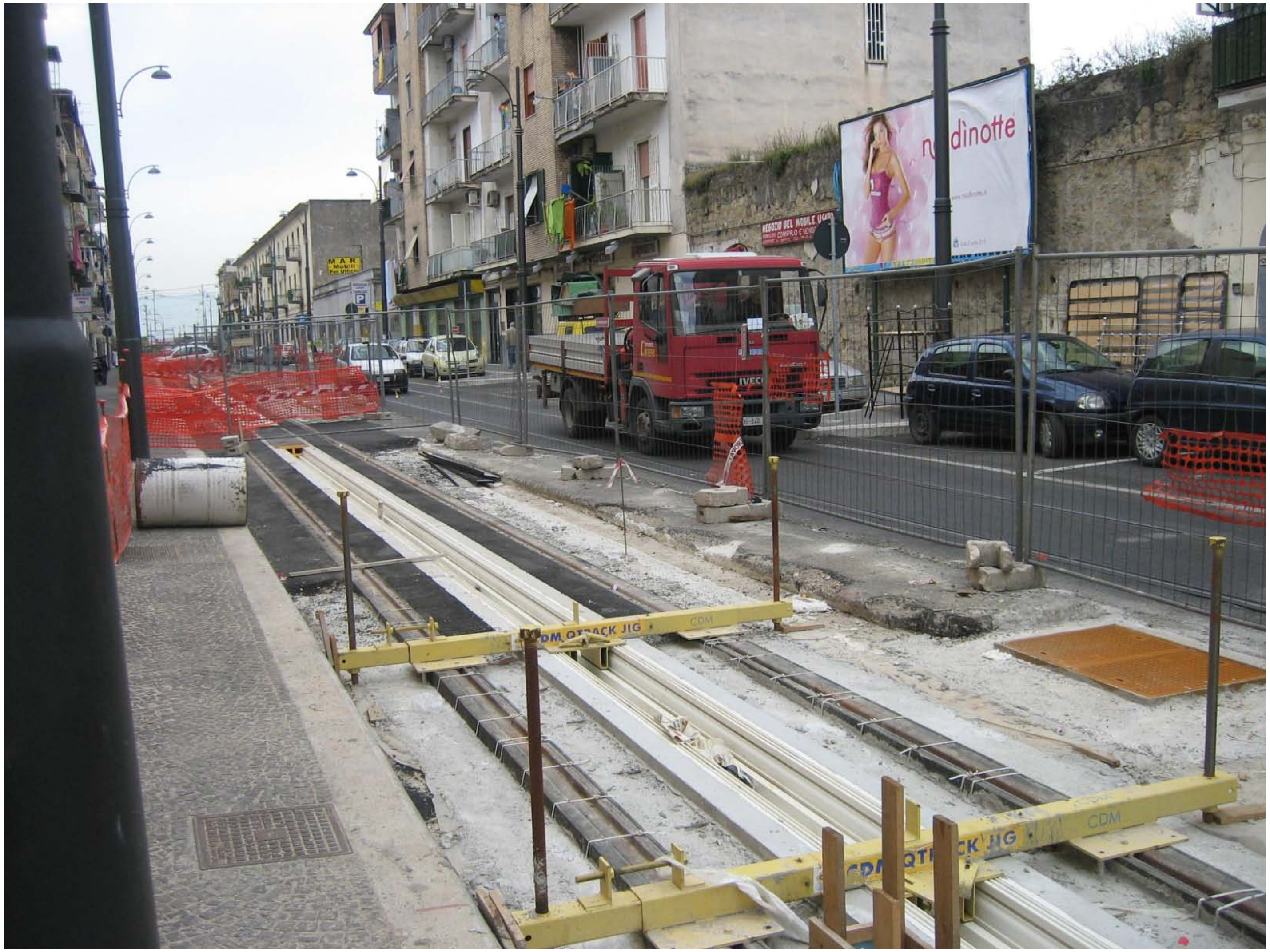
Making your world a quieter place



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

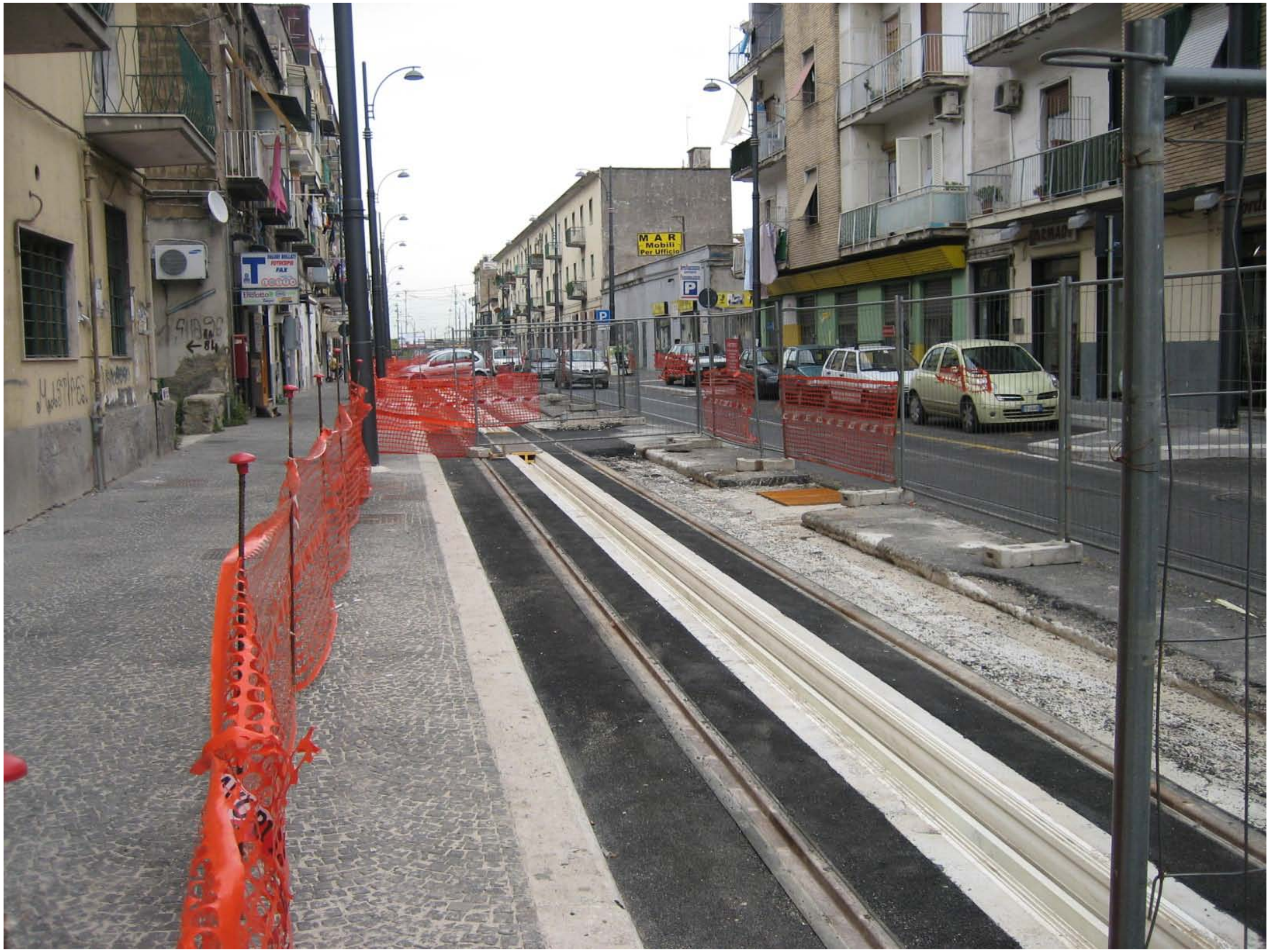
Making your world a quieter place



Phase II – Napoli Via Stadera Installation

Phase II – On Site Installation: Concrete phase 4 & Asphalt & Malta

Making your world a quieter place



Conclusion

New opportunities for CDM

Making your world a quieter place

- ASTS is now very interested to collaborate furthermore with CDM in different projects with and without the CDM-QT-JIG-TRAMWAVE system:
  - Lusail (Qatar)
  - Copenhagen
  - Italian, European and Worldwide projects …

THANK YOU FOR YOUR ATTENTION

Making your world a quieter place

Thank you for your attention

58TH UITP World Congress

Public transport: making the right mobility choices

Vienna 7 > 11 June 2009

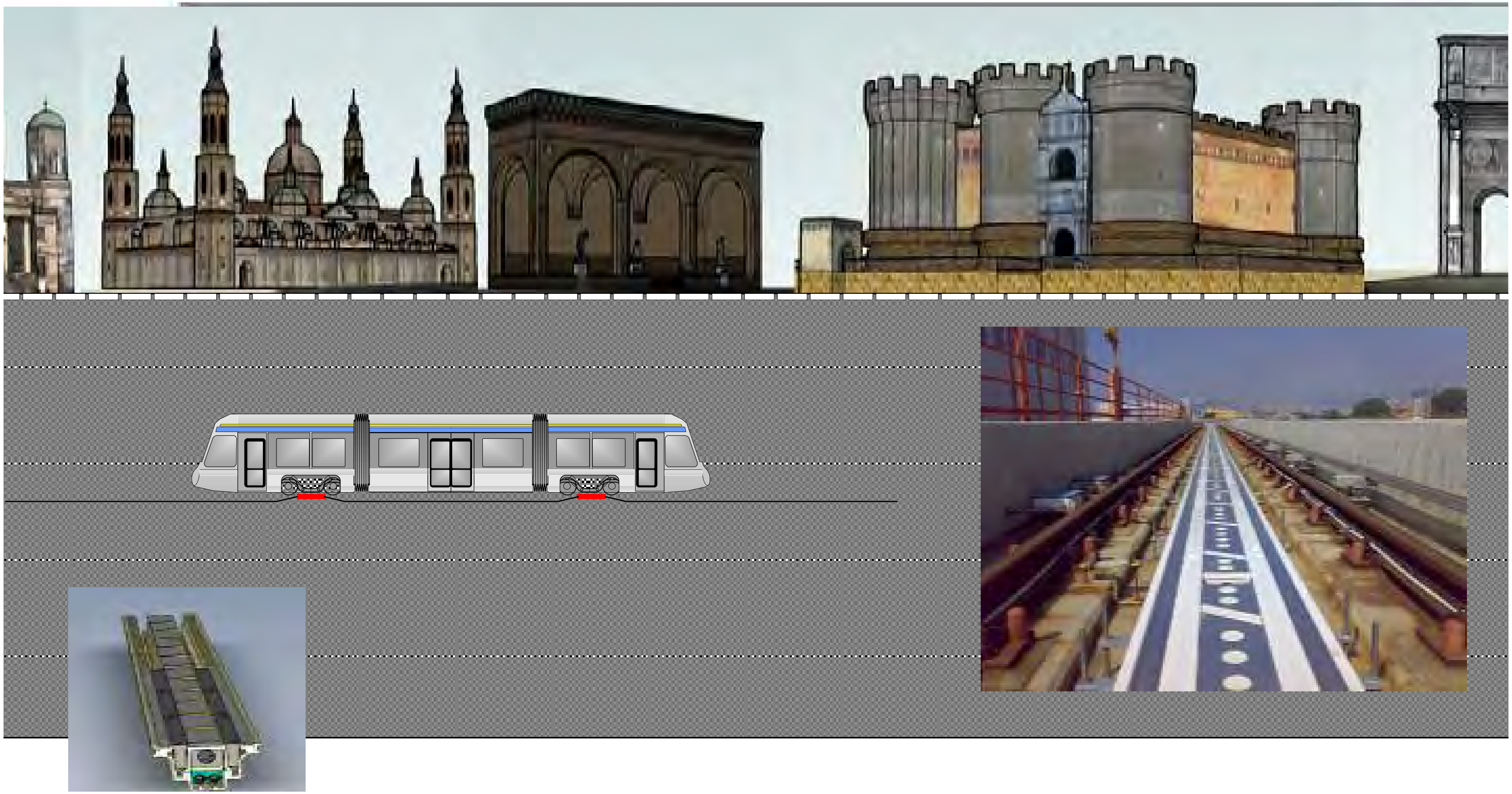
TramWave

AnsaldoSTS

A Finmeccanica Company

AnsaldoSTS
A Finmeccanica Company

TramWave



The Ultimate CATENARY FREE TRAMWAY SYSTEM

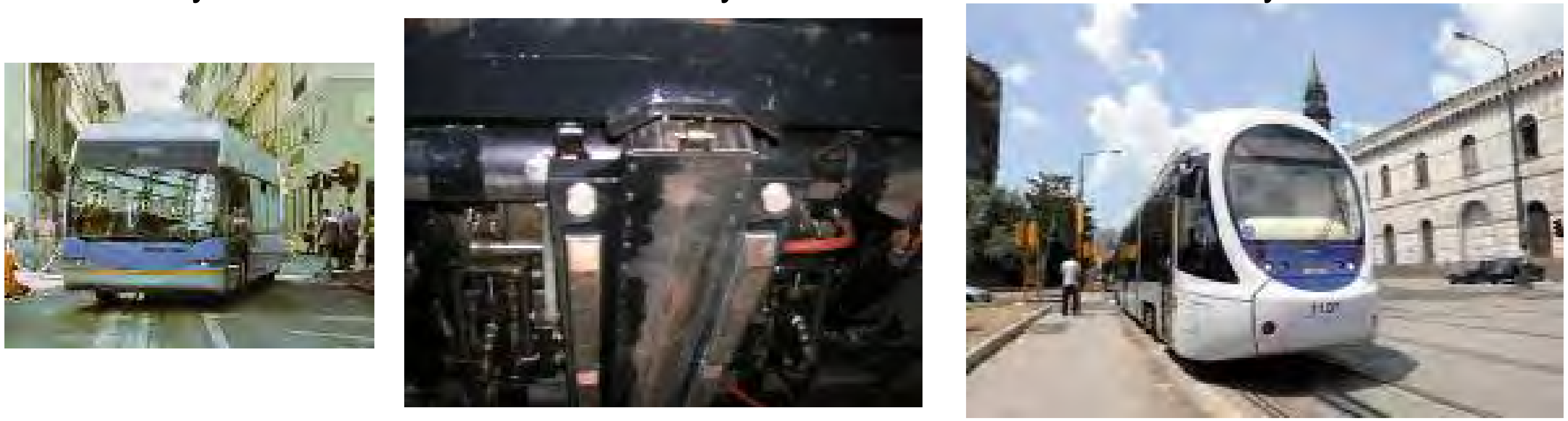
TramWave

Ansaldo STS pioneered the modern technology for transit systems without overhead catenary.

- First prototype development: year 1998
- First pilot plant of intermediate transit systems: year 2000
- First test of ASTS technology for a rail vehicle: year 2000

TramWave is now a product:

- Particularly focused and developed for different tramway systems
- Based on a “core technology” well proved and tested
- Presently customized for “SIRIO” tramway breed but able to be fitted on any tram



TramWave

Ansaldo STS technology is founded on the following concepts:

- *Use of a "closed conduit", embedded on the ground*
- *Transmission of power through a segmented surface contact line, where each segment is insulated and normally connected to ground.*
- *Simple physical principles are governing the whole operation of the system.*
  - *The contact segments are switched on to the positive feeder only by the presence of the power collector over the contact line, by means of the pulling force of a "built in" permanent magnet on a flexible ferromagnetic belt, located inside the conduit.*
  - *The contact segments are switched off to negative feeder by the same flexible ferromagnetic belt that falls down by gravity force*
  - *The total length of the segments that are in live condition is very short (1 meter max), reducing to the minimum the "unsafe" area, (allowing the use of the technology even for short length vehicles).*
  - *The safety of the system is assured in all the possible normal and upset operating condition.*

TramWave

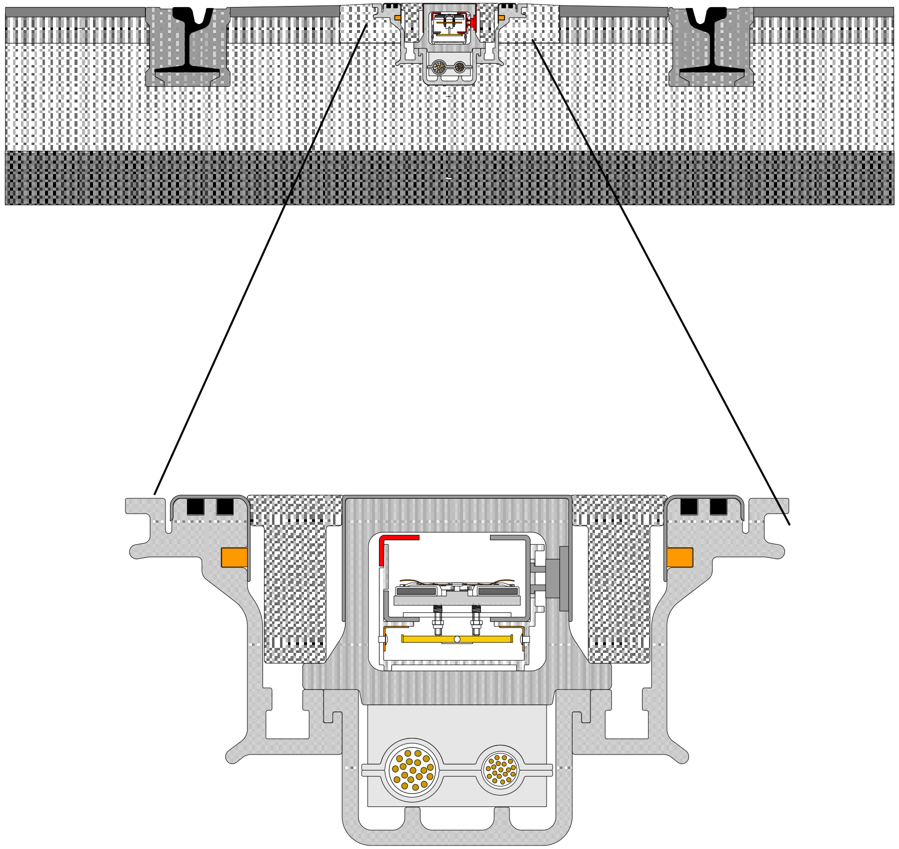
- The system technology is specially designed and manufactured to facilitate the installation of all the system components:
  - in a new plants and vehicles
  - as retrofit in already existing installations.

Many different operational and functional configurations may be envisaged.

TramWave

The “Tramwave” power line can be easily installed between the running rails.

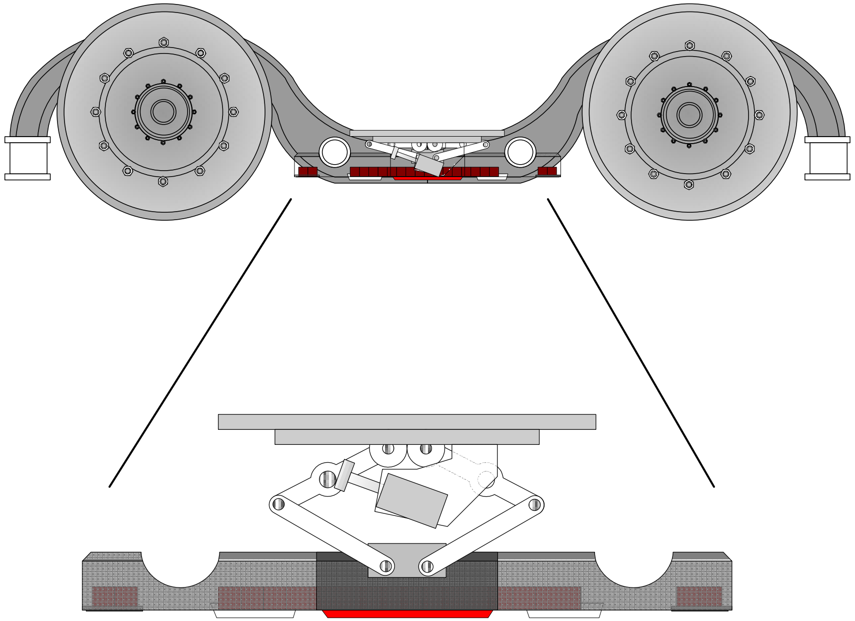
- *The section of the power line is very compact.*
- *The overall dimensions are of the line components are compatible with a wide range of track equipments*
- *All the main components of the power line are located inside the line section.*
- *The traction current could return on the same power line, without involving the running rails*
- *No need of special protection against stray currents*
- *No electromagnetic emission inside or outside the vehicle.*



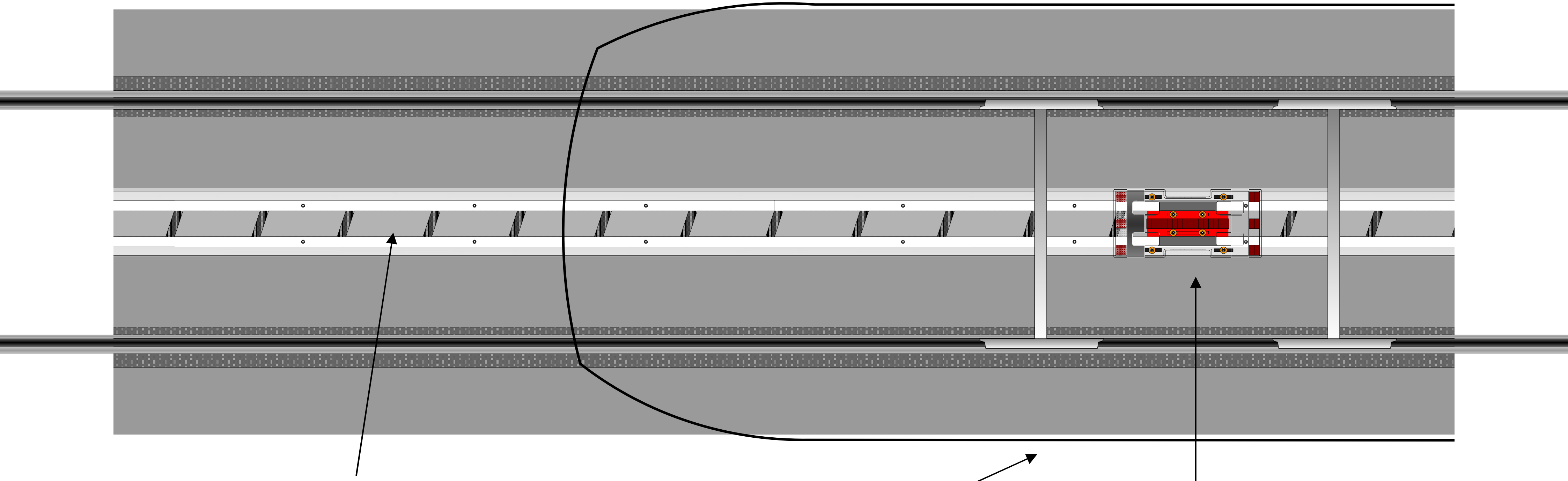
TramWave

The overall dimensions and functional characteristics of “TramWave” power collector are enough compact to be inserted inside a tram bogie, or, if necessary, under the vehicle body.

- *The power collector is lifted up and down over the contact line by a special pantograph.*
- *The interfacing of the power collector/pantograph with the vehicle bogie and the other parts of the vehicle is very simple and could be studied and rearranged for different types of bogies.*
- *A simple command equipments could manage the global operation of the power collector, power sources switching, etc.*



Tramwave components

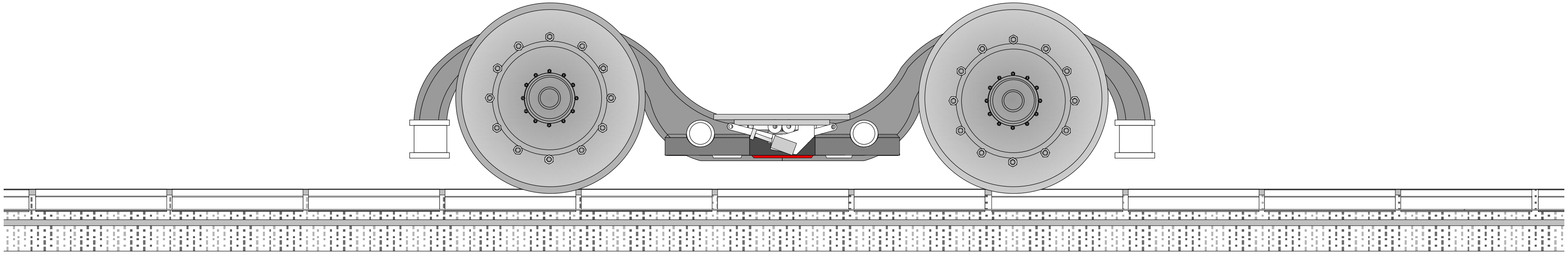


Power Line

Vehicle body

Magnetic power collector

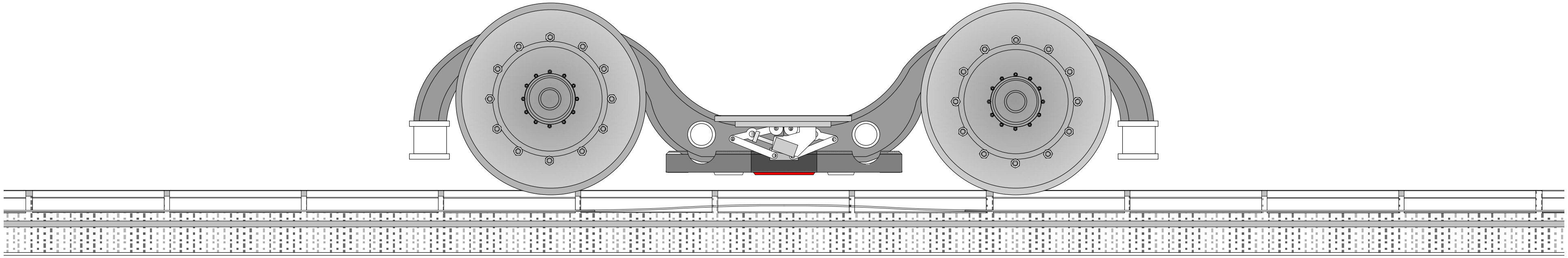
TramWave



When the pantograph is retracted in rest position:

- *The magnetic power collector in the upper position is unable to activate the power line segments; the pulling force is not enough to lift up the belt.*
- *The vehicle can run over the line without activating the segments*
- *All the segments stay connected to ground.*

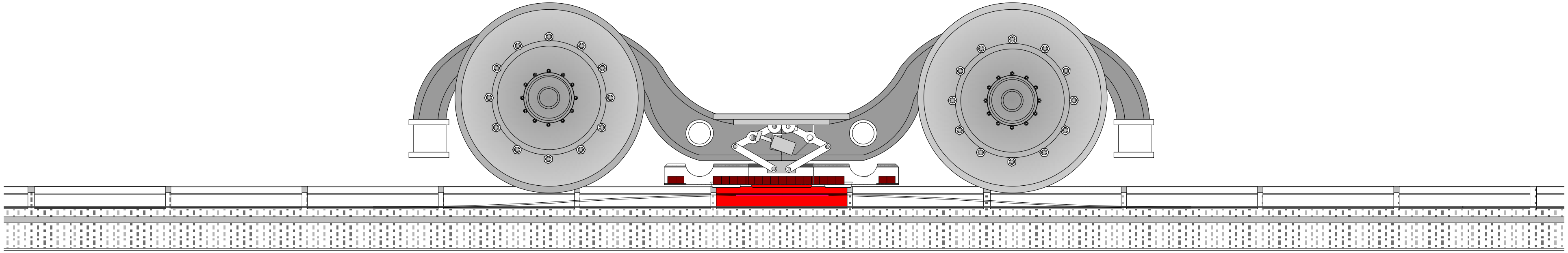
TramWave



When the pantograph is released:

- *the power collector goes down to the line*
- *the pulling force increase and induces the rising of flexible belt inside*
- *some segments (1-2-3) under the power collector are disconnected from ground.*

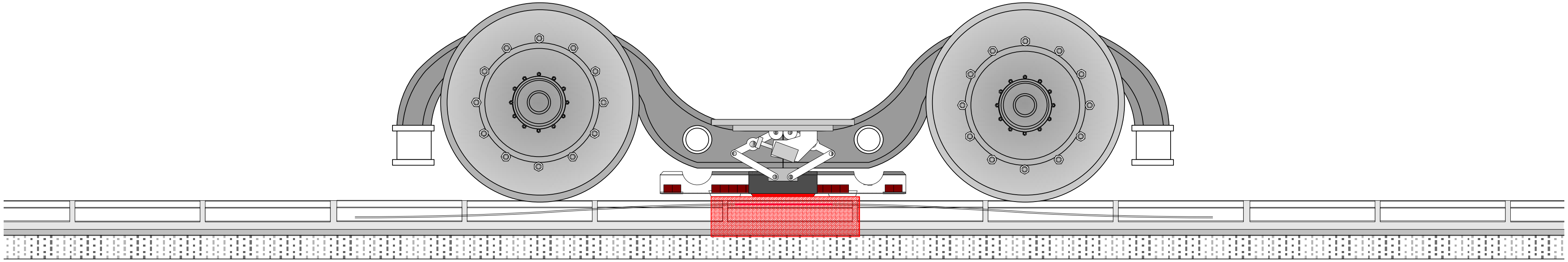
TramWave



When the pantograph is completely released :

- *the power collector is in contact with the line segments*
- *the flexible belt reaches its working position and activates the underlying segment (s)*

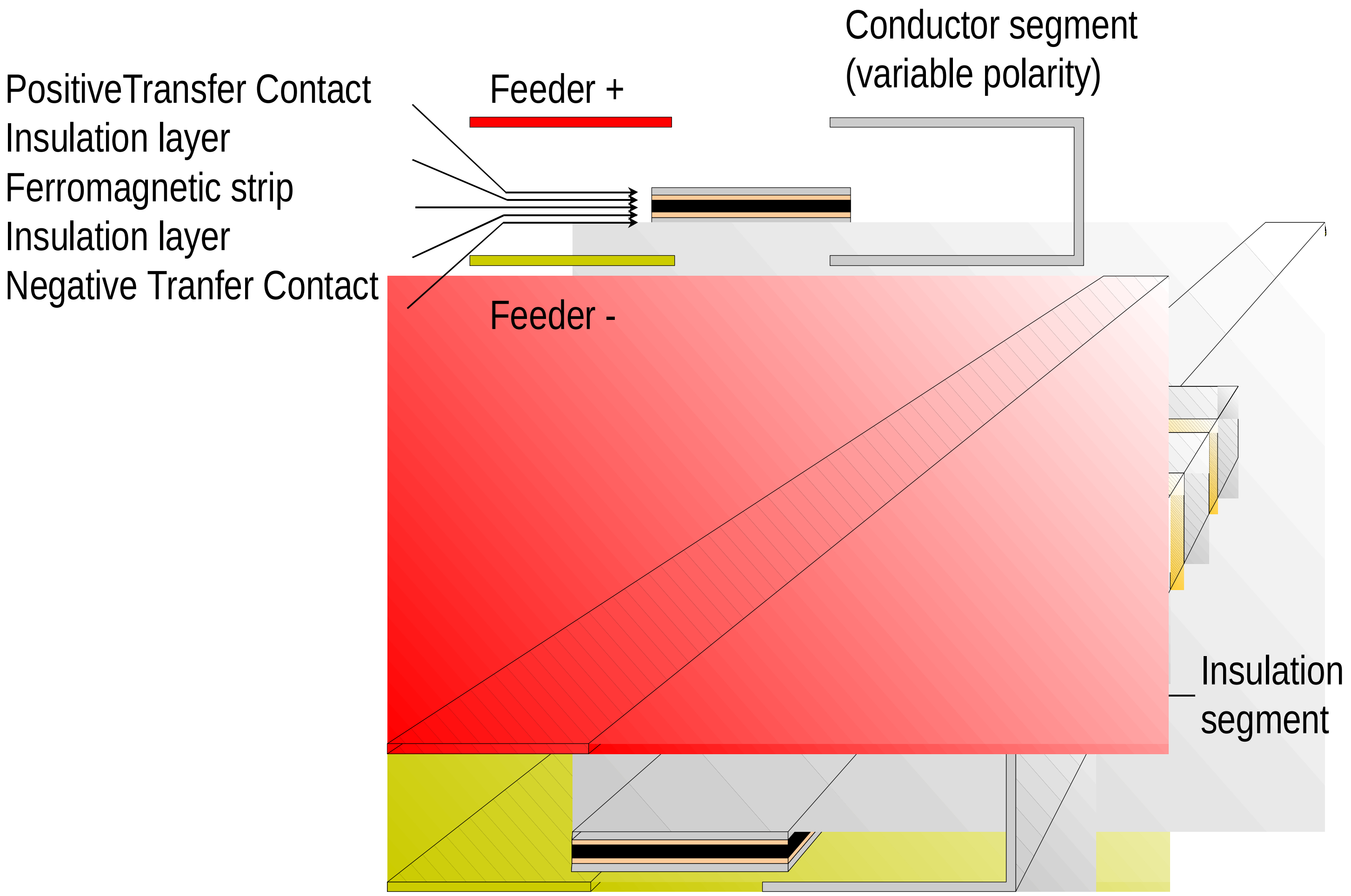
TramWave



The vehicle is ready to run, powered by the line.

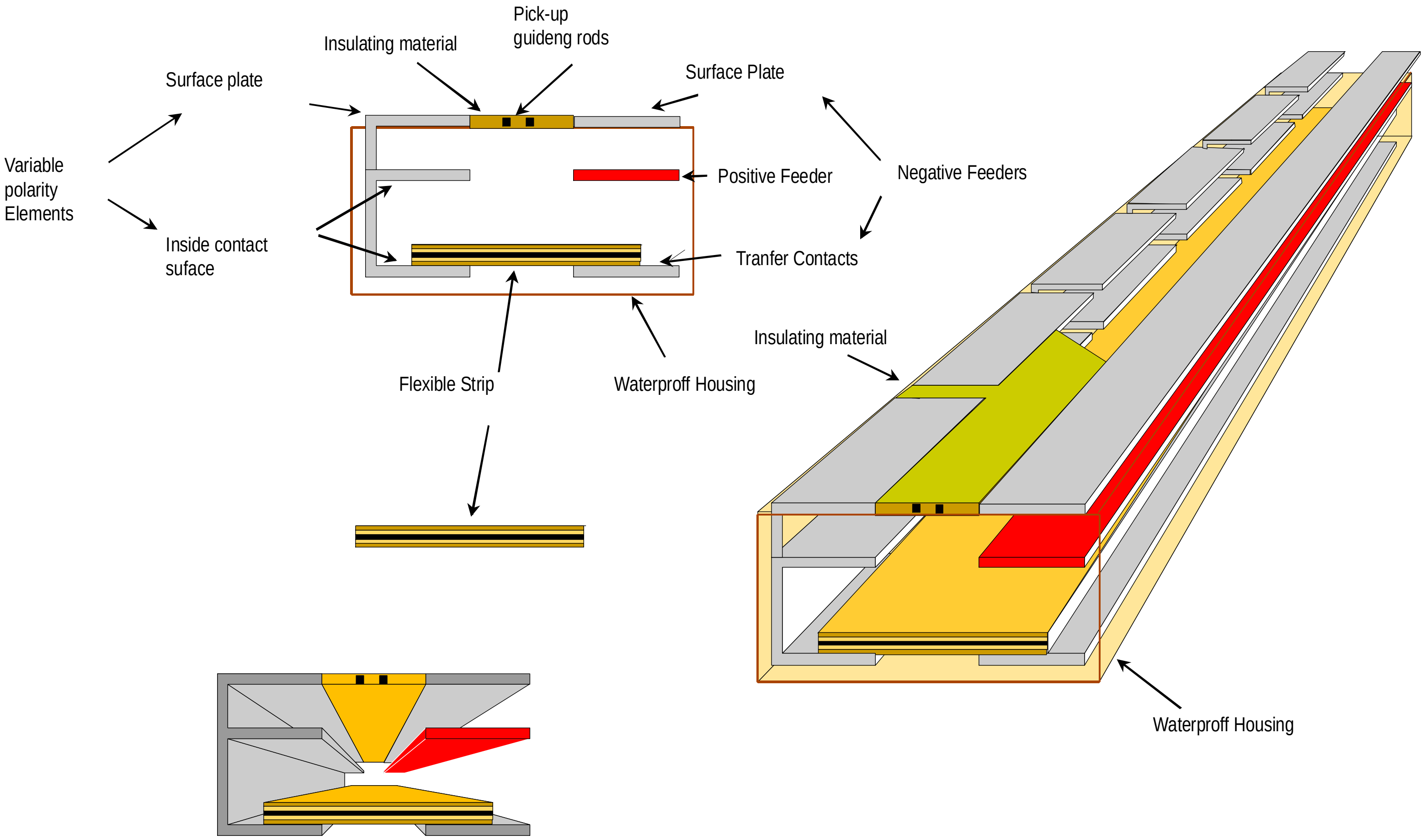
Operating principles

TramWave

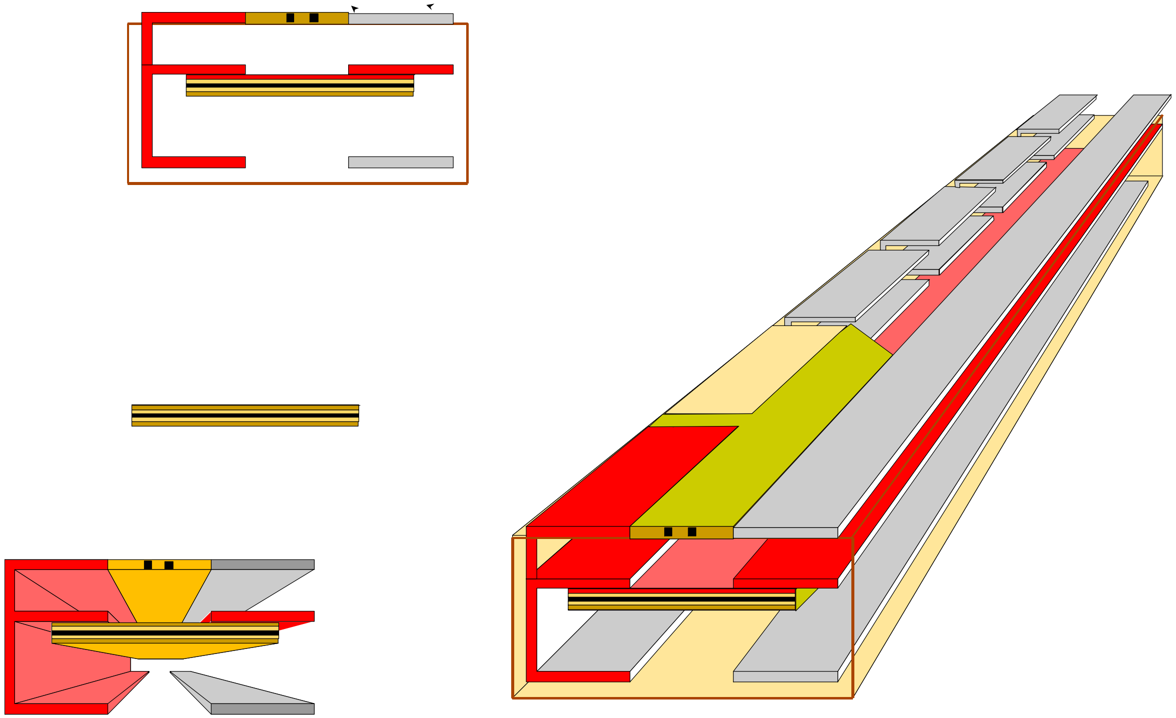

Conductor segment
(variable polarity)
PositiveTransfer Contact
Insulation layer
Ferromagnetic strip
Insulation layer
Negative Tranfer Contact
Feeder +
Feeder -
Insulation
segment

TramWave

Concept



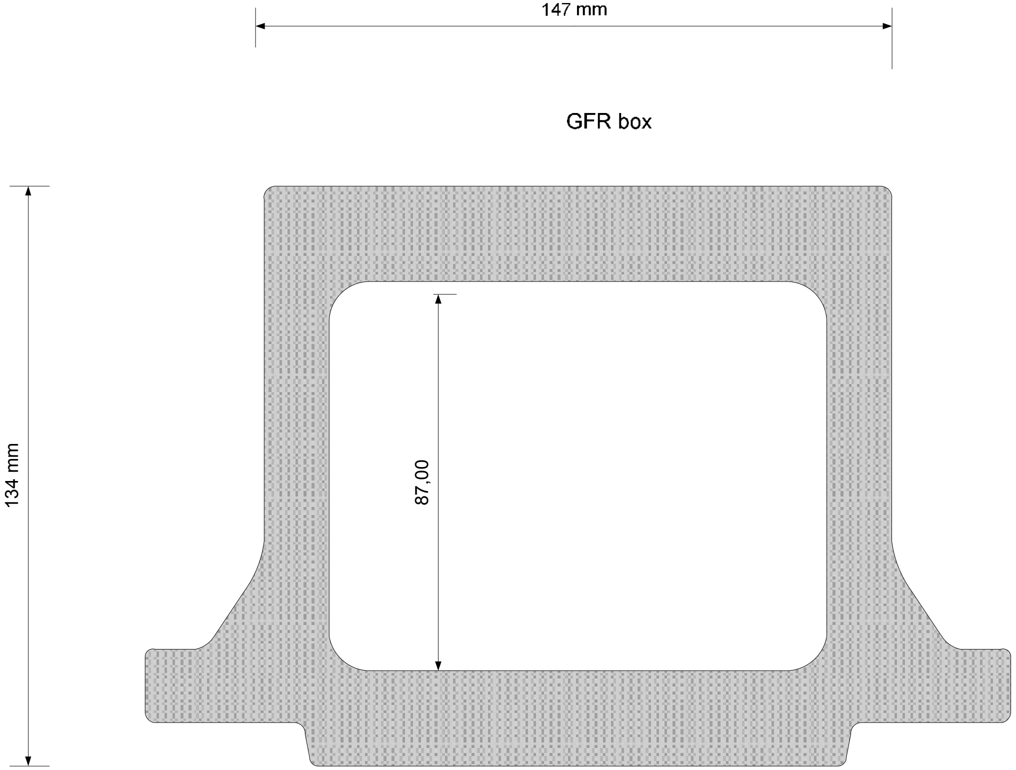
Concept



Main components

Module section

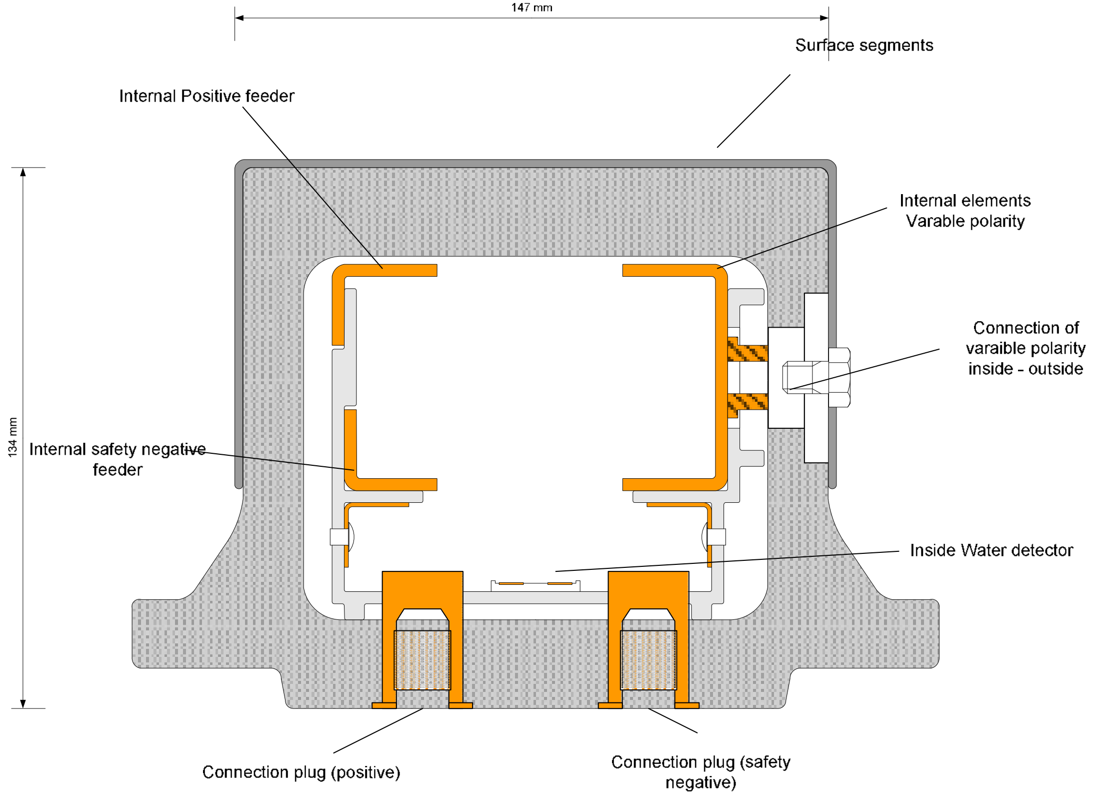
The Module



TramWave

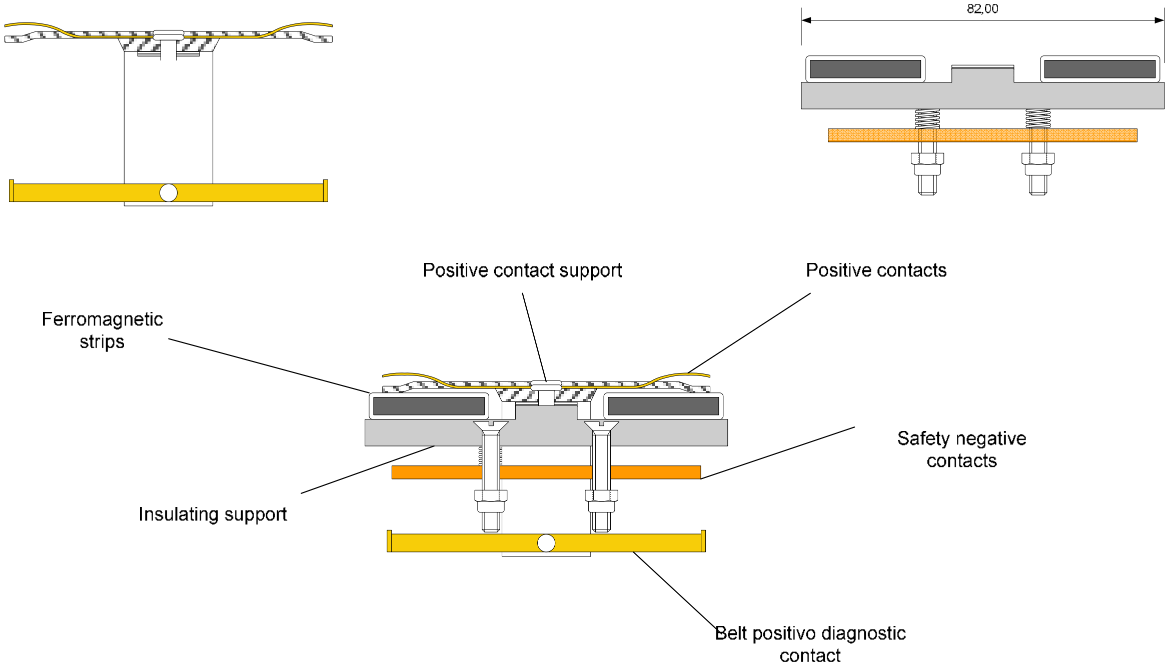
The module: Internals – Fixed elements

The module fully equipped

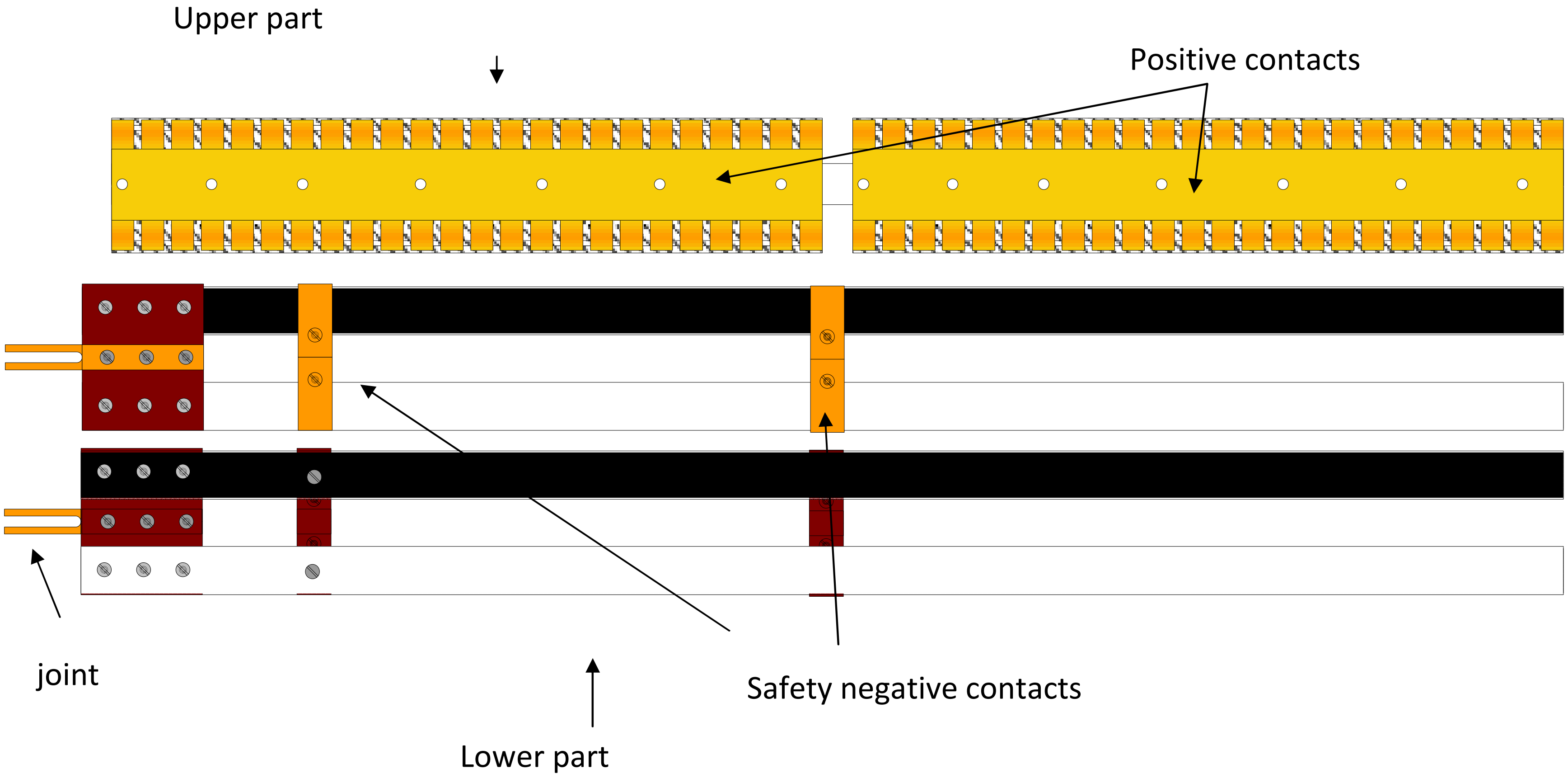


The flexible belt and contact carrier

The Module
The flexible belt

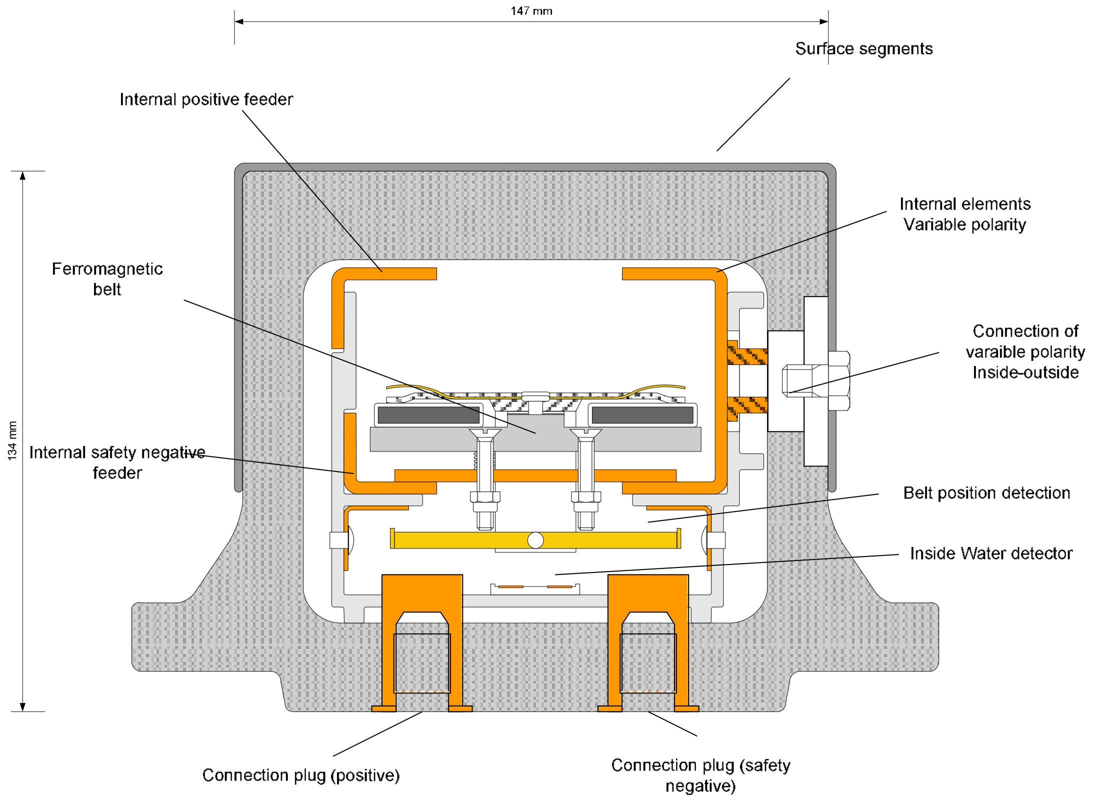


The flexible belt and contact carrier



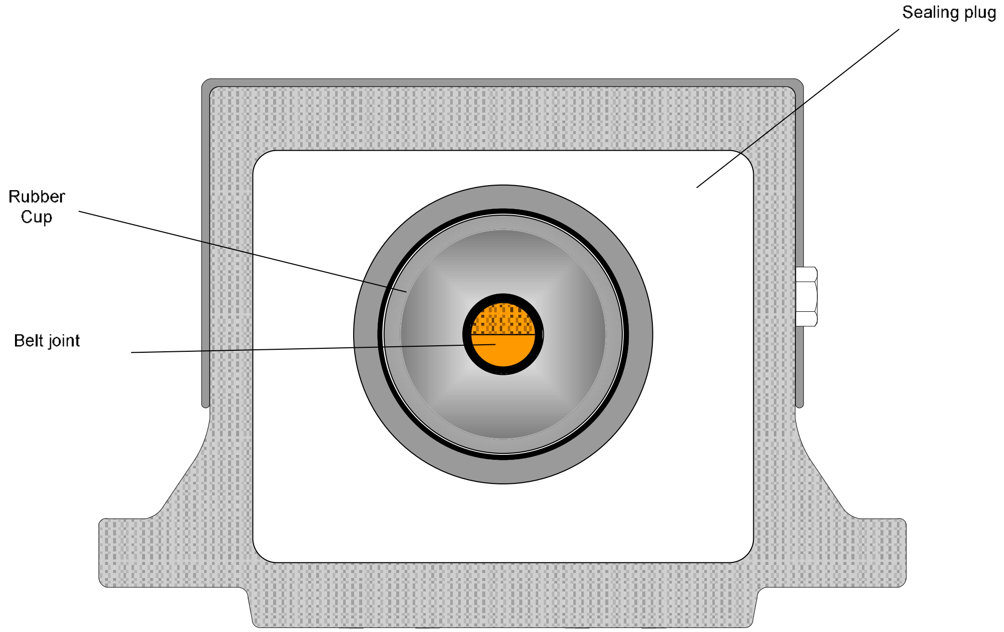
The module: global section

The Module Section



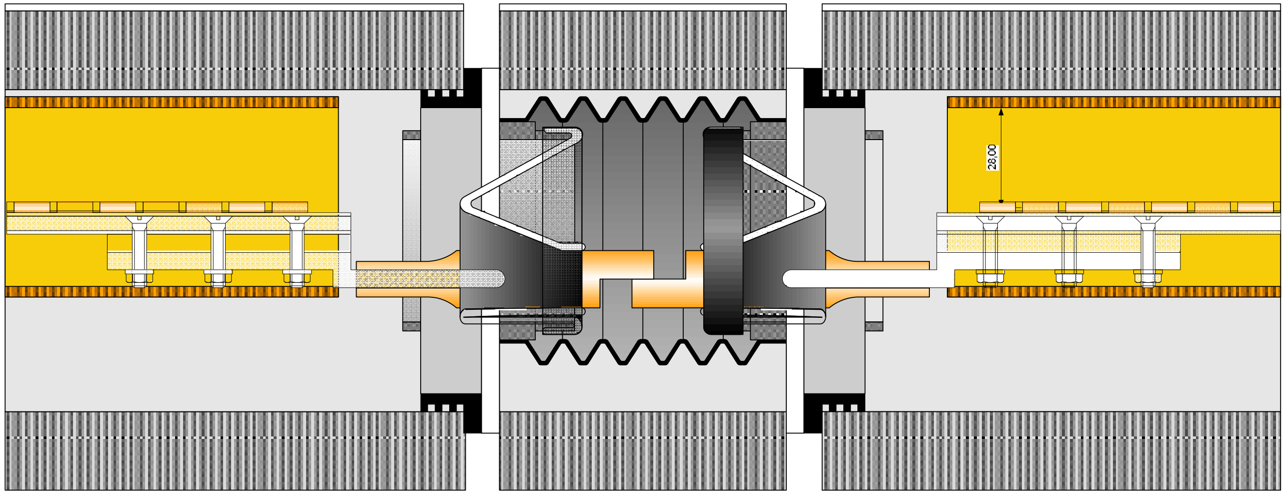
The module

End terminations



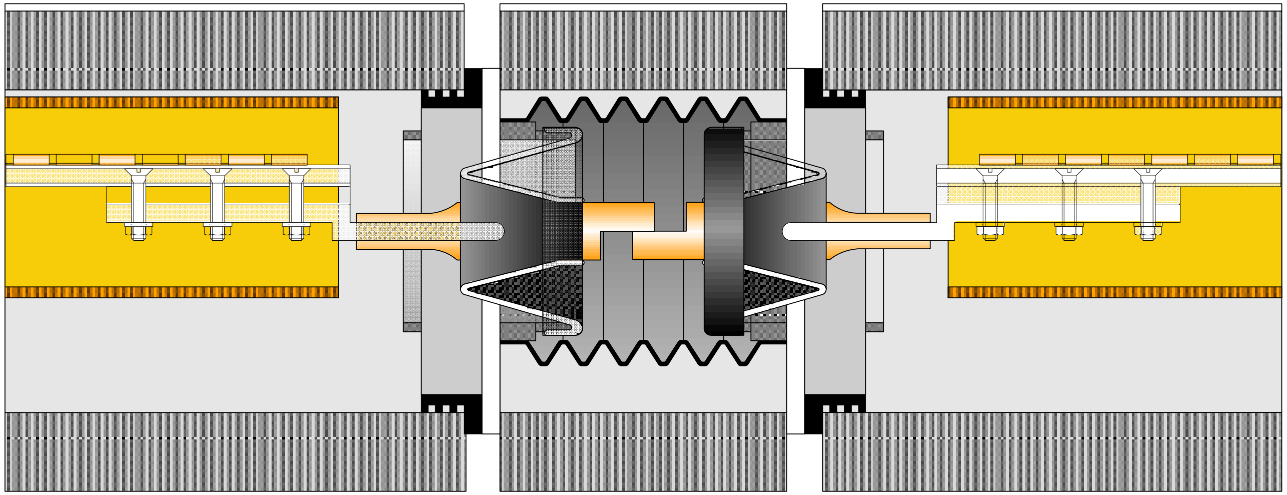
TramWave

Joints between adjacent modules

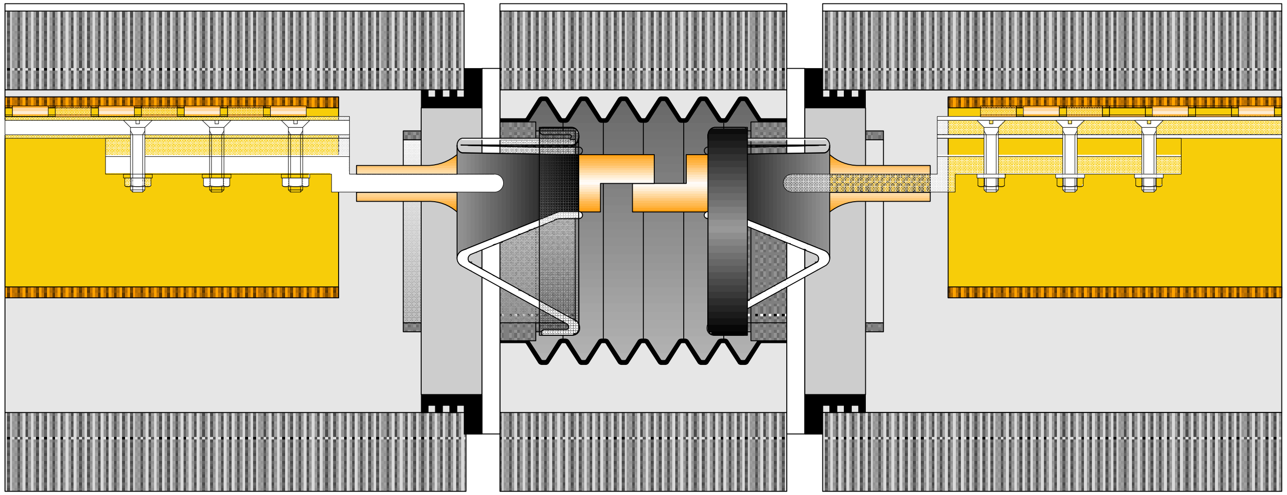


Rest condition

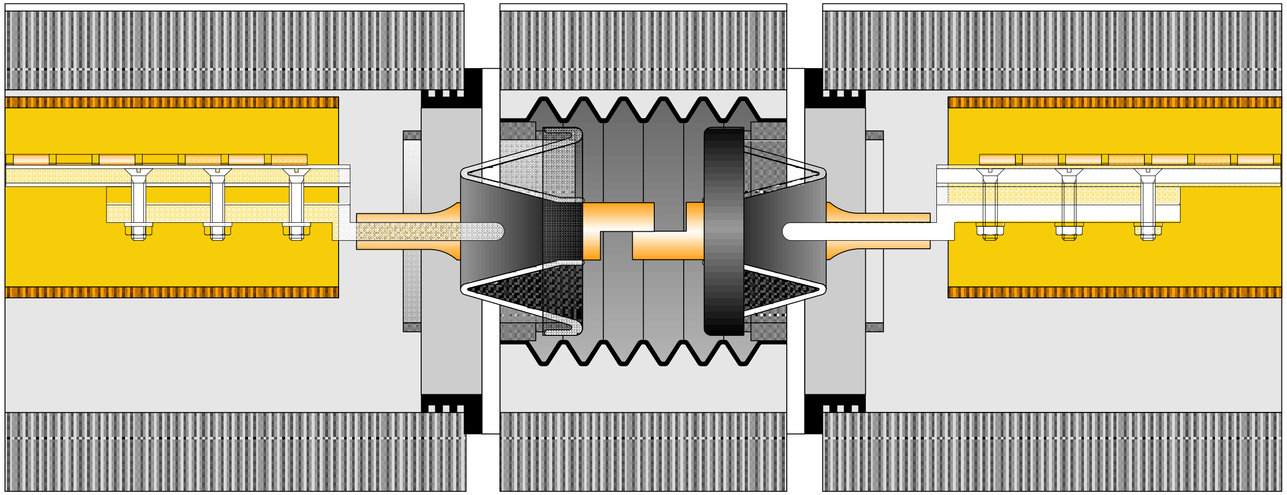
TramWave



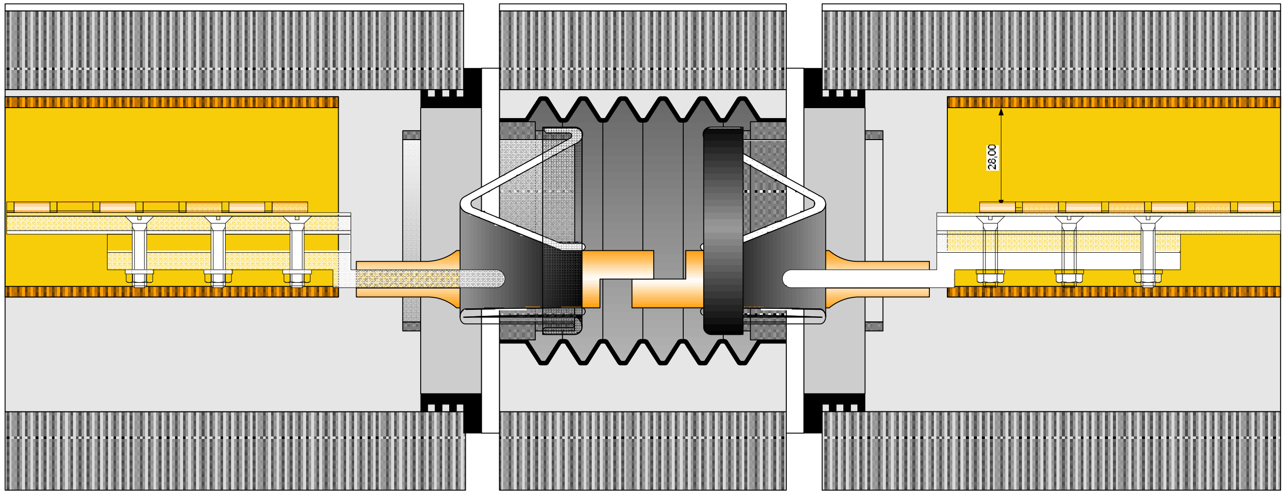
TramWave



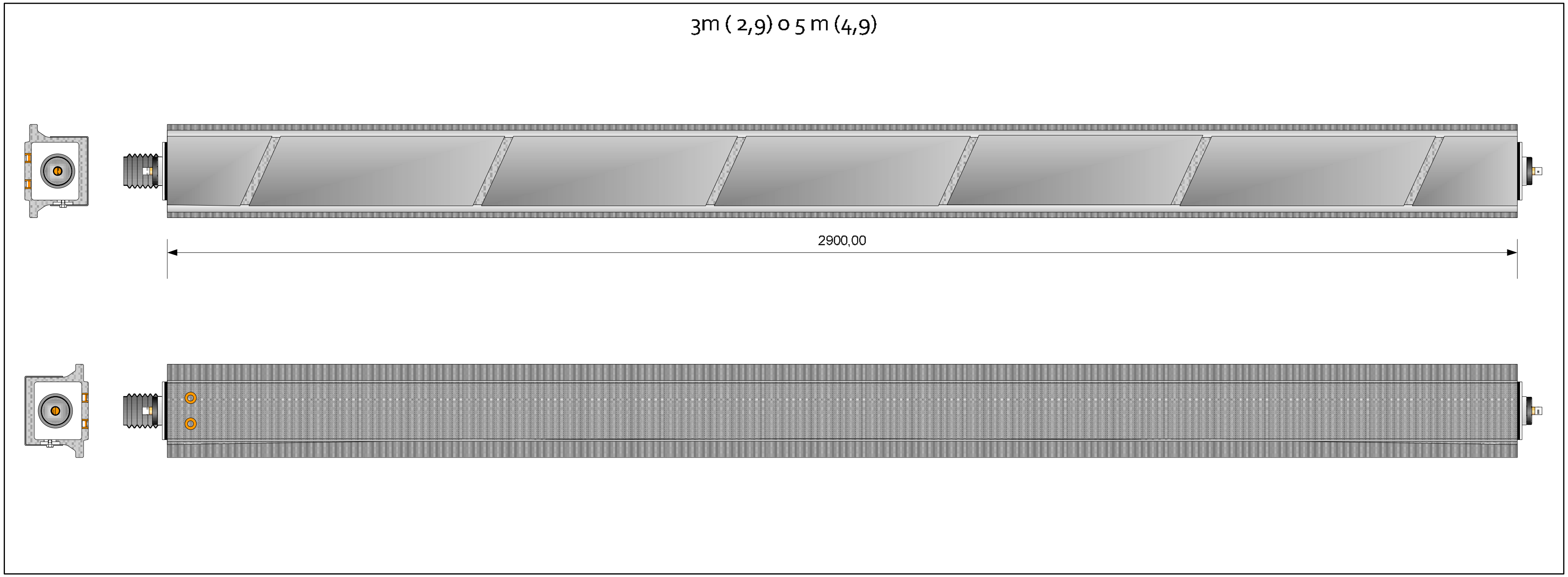
TramWave



TramWave

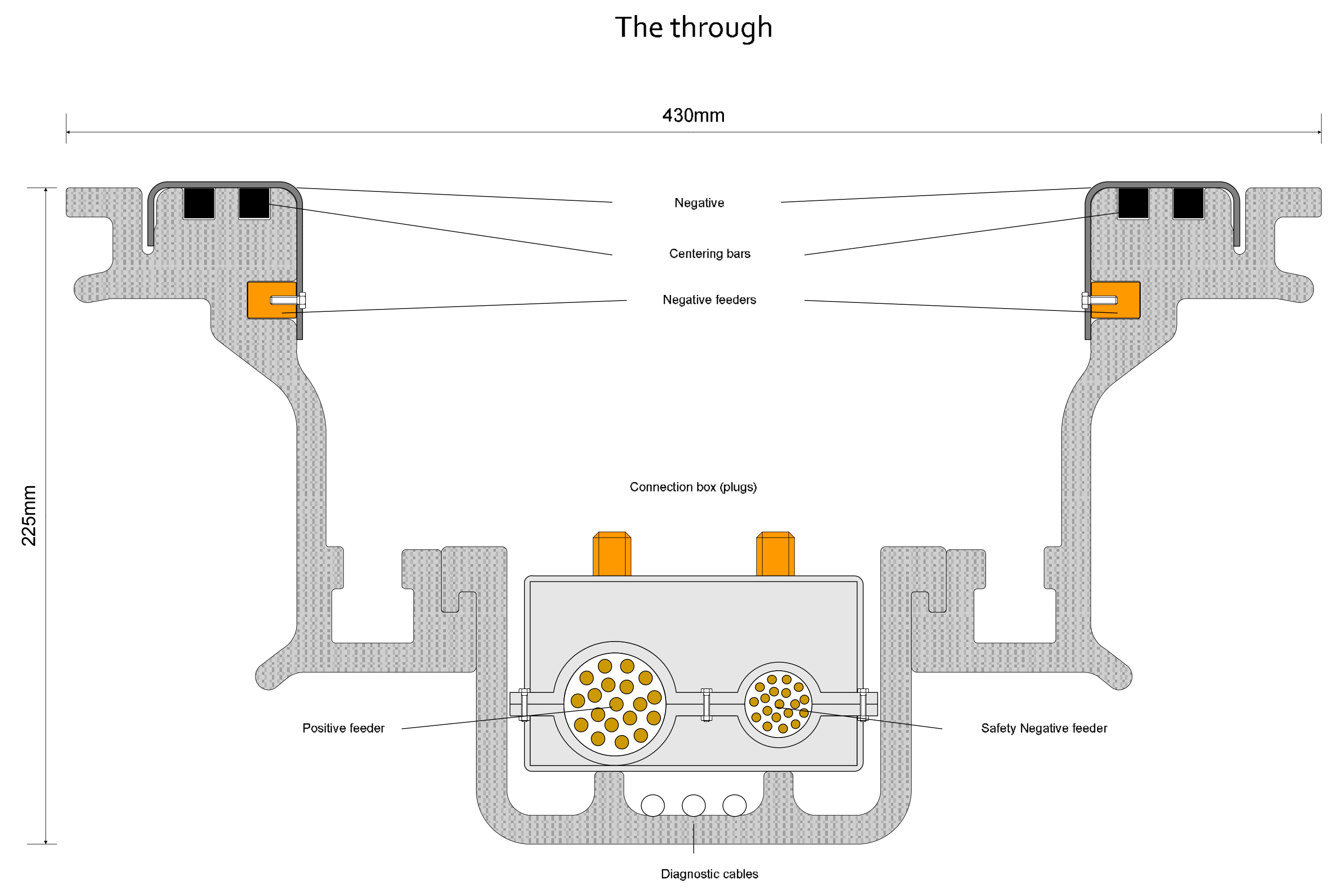


The module fully assembled



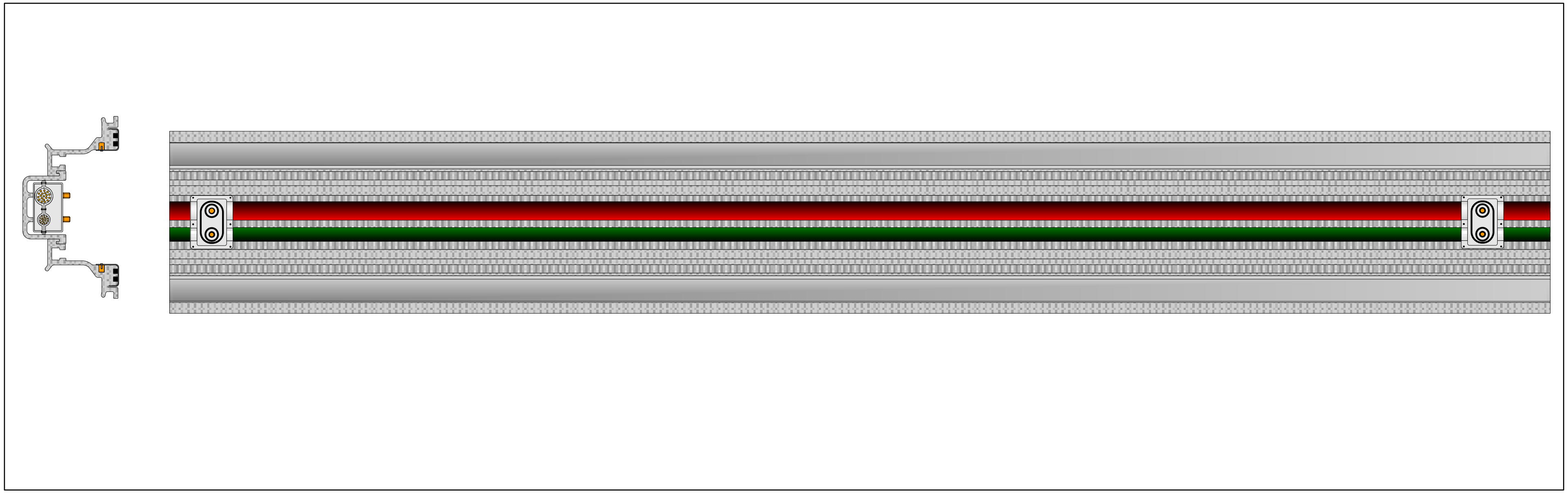
TramWave

The open conduit (the trough) Section



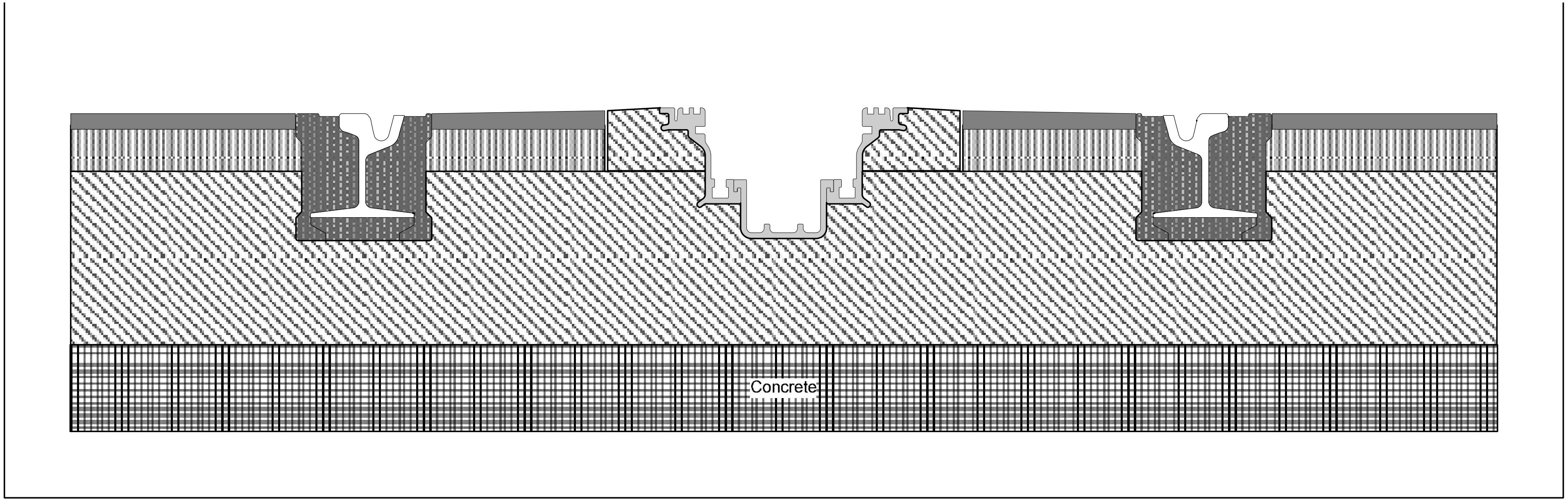
TramWave

The open conduit (the trough) Top View



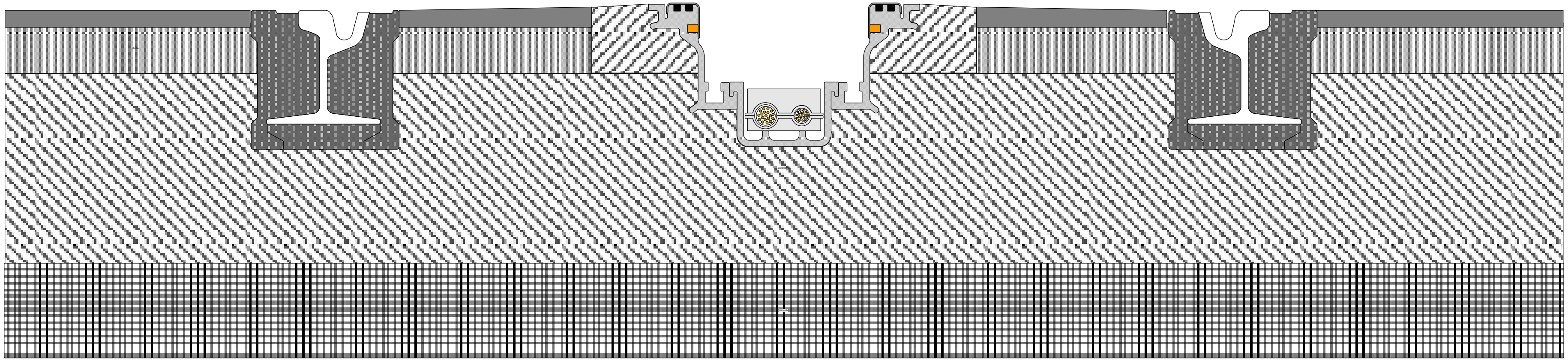
TramWave

Example of trough insertion in the track



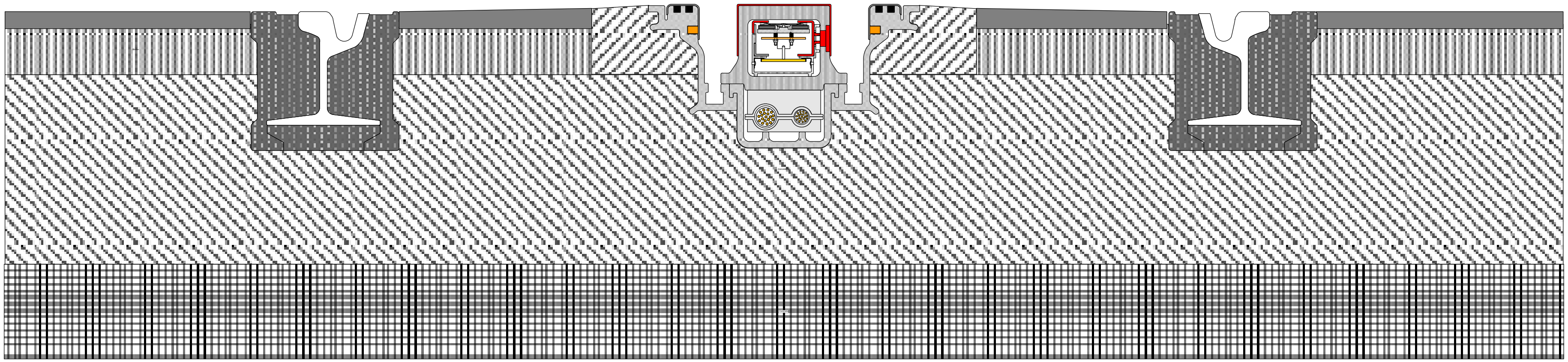
TramWave

The power line ready fot insertion of the modules



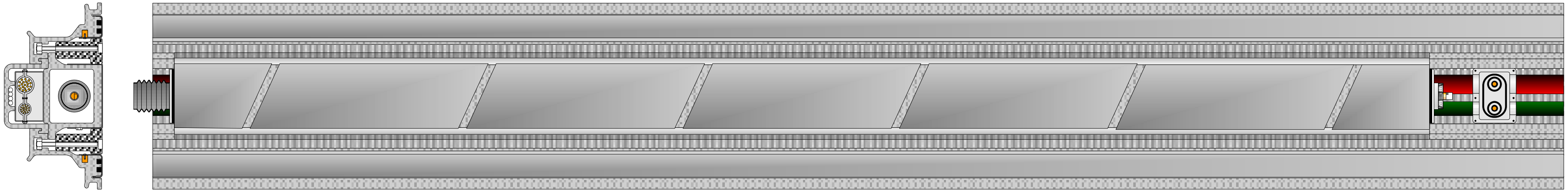
TramWave

The module in the trough (section)



TramWave

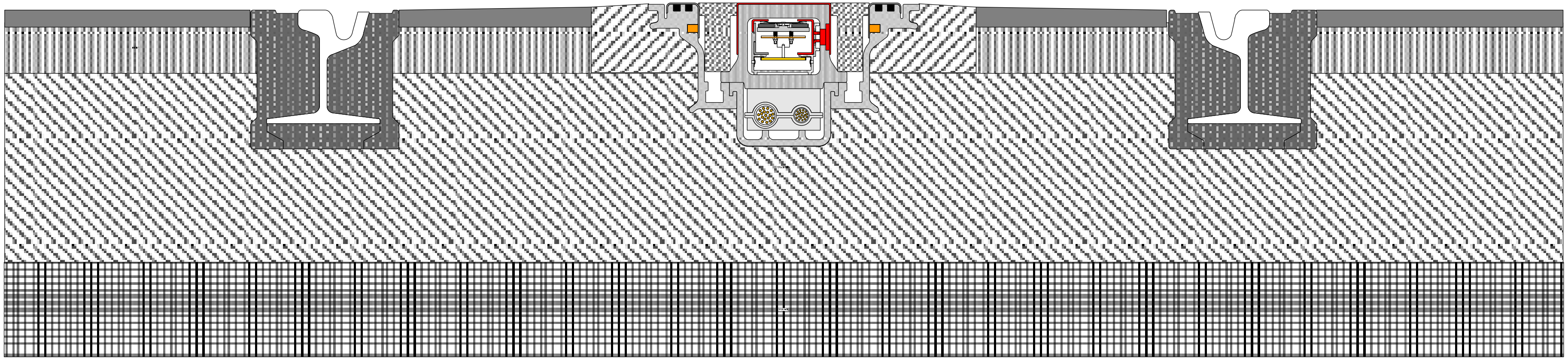
The module in the trough (top view)



TramWave

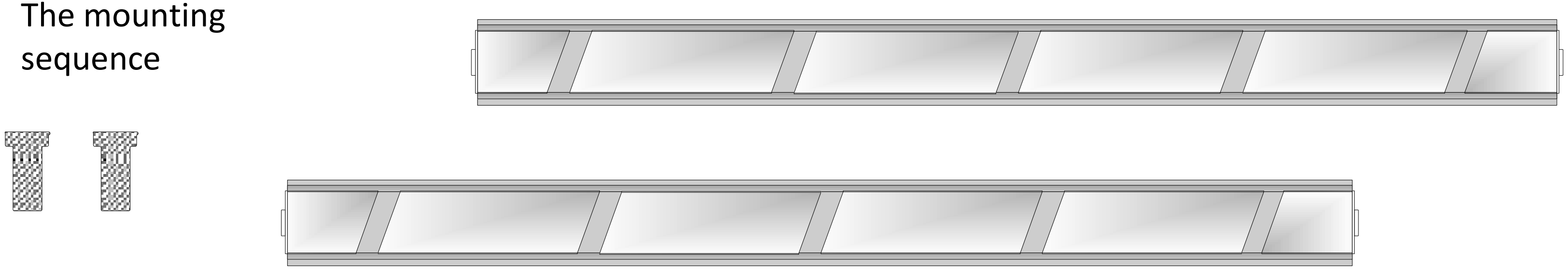
The line fully equipped

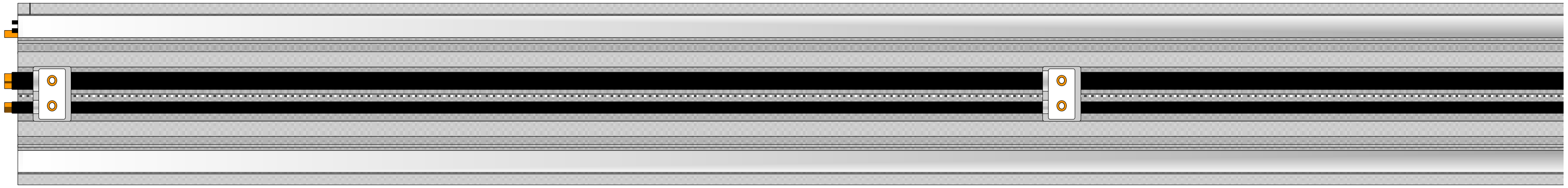
(section)

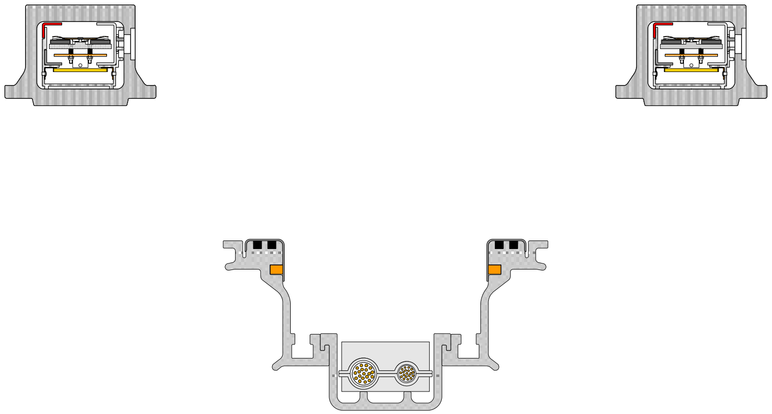


TramWave

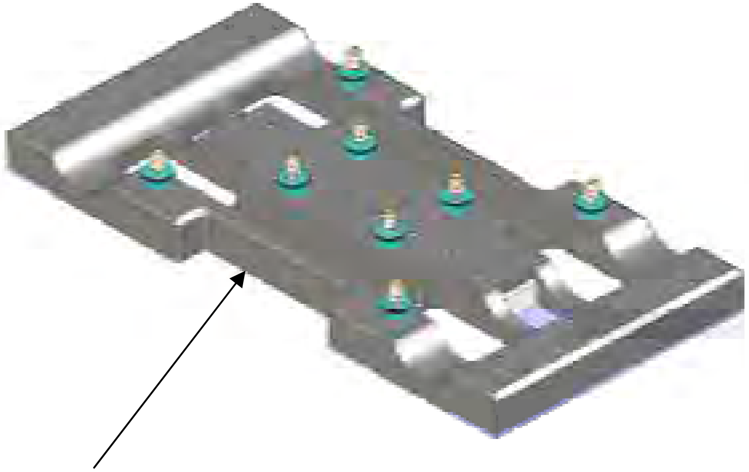
The mounting sequence

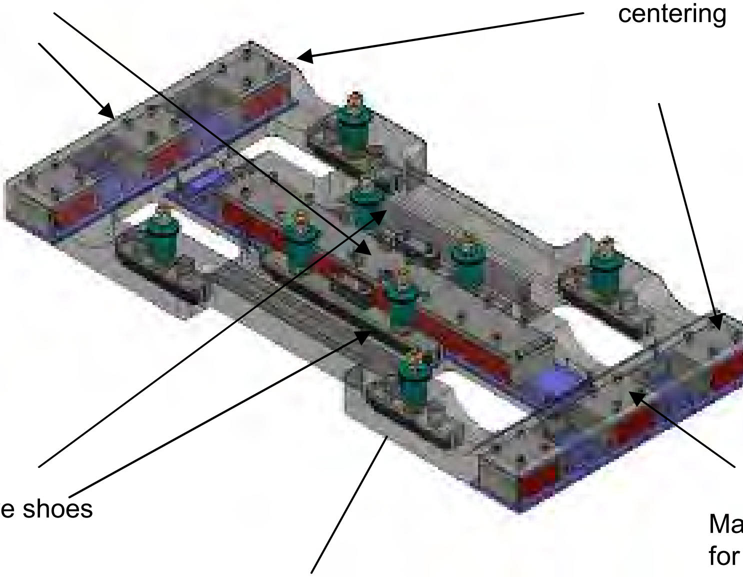






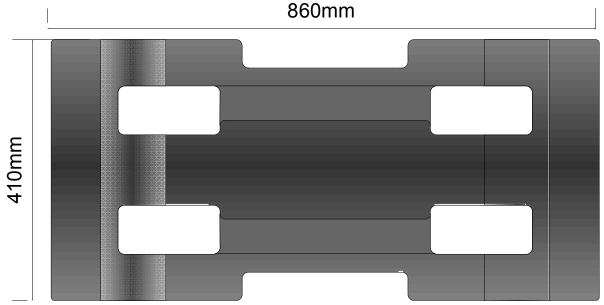
The magnetic power collector




Magnet blocks for belt lift up
Magnetic blocks for centering
Positive shoes
Negative shoes
Magnet blocks for belt lift up

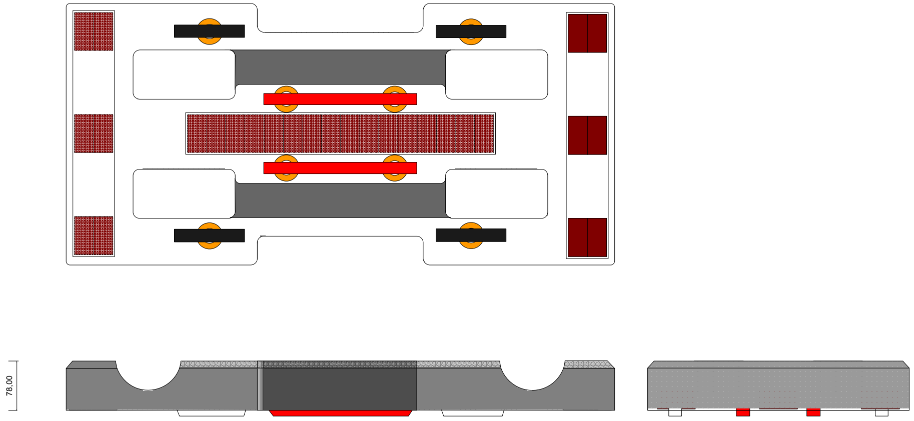
TramWave

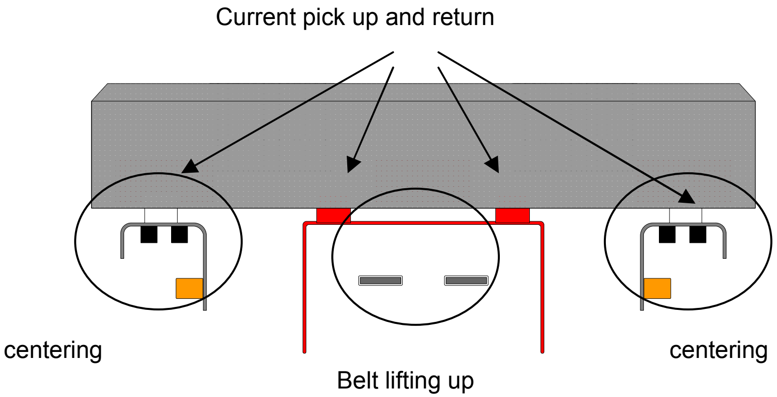
The magnetic power collector



Three main function

- Activation of line segments
- Current pick up and current return
- Guide the power collector over the line





TramWave

- The length of the magnet, the pulling force, the characteristics of flexible belt (allowed internal gap, rigidity, weight) are designed to assure:
  - *Adequate inner contact length for necessary current in any static or dynamic conditions.*
  - *The correct sequence of activation of segments.*

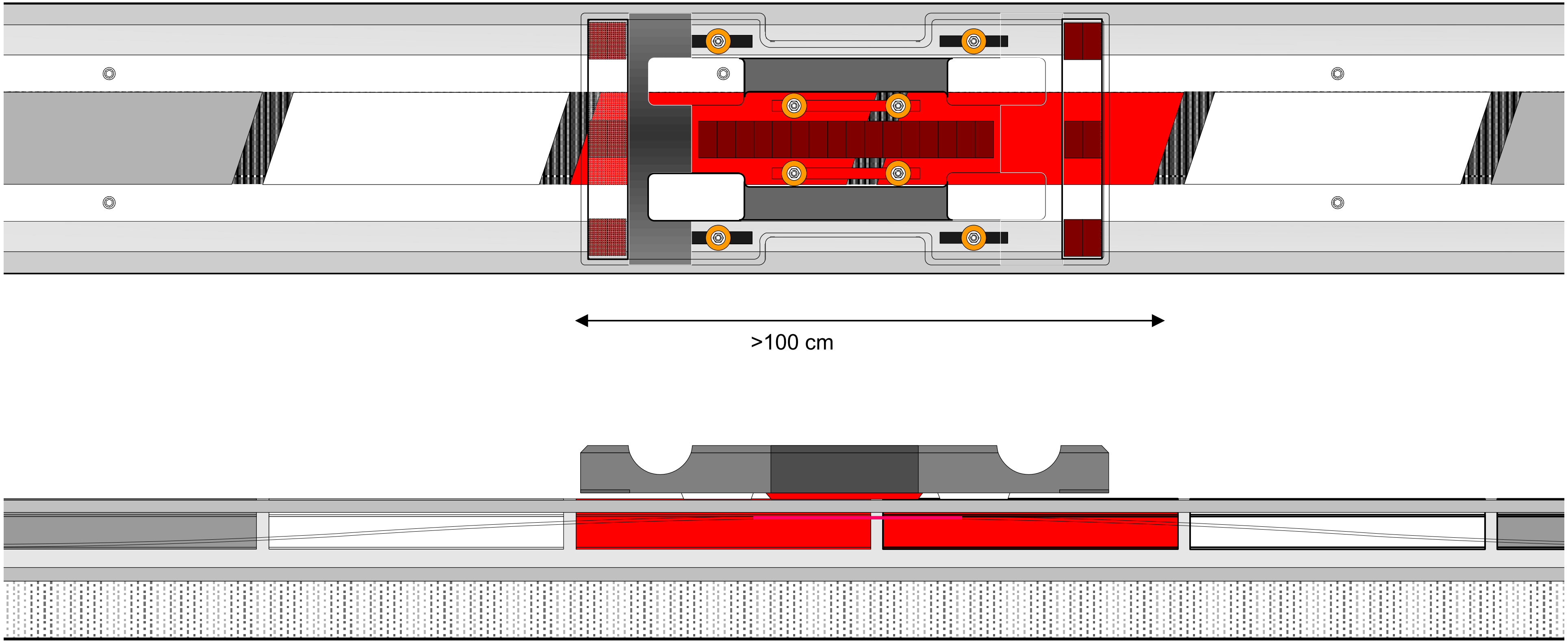
- The total length of the “wave”, is no more than 3 meters
  - *No constraints for the position of the power collector on the bogies*
  - *No limits to place two or three power collector on the vehicle*
  - *The area to be protected is very limited (less than 1 m x 270 mm)*

- The inner contacts are segmented for a better insulation of non activated segments.

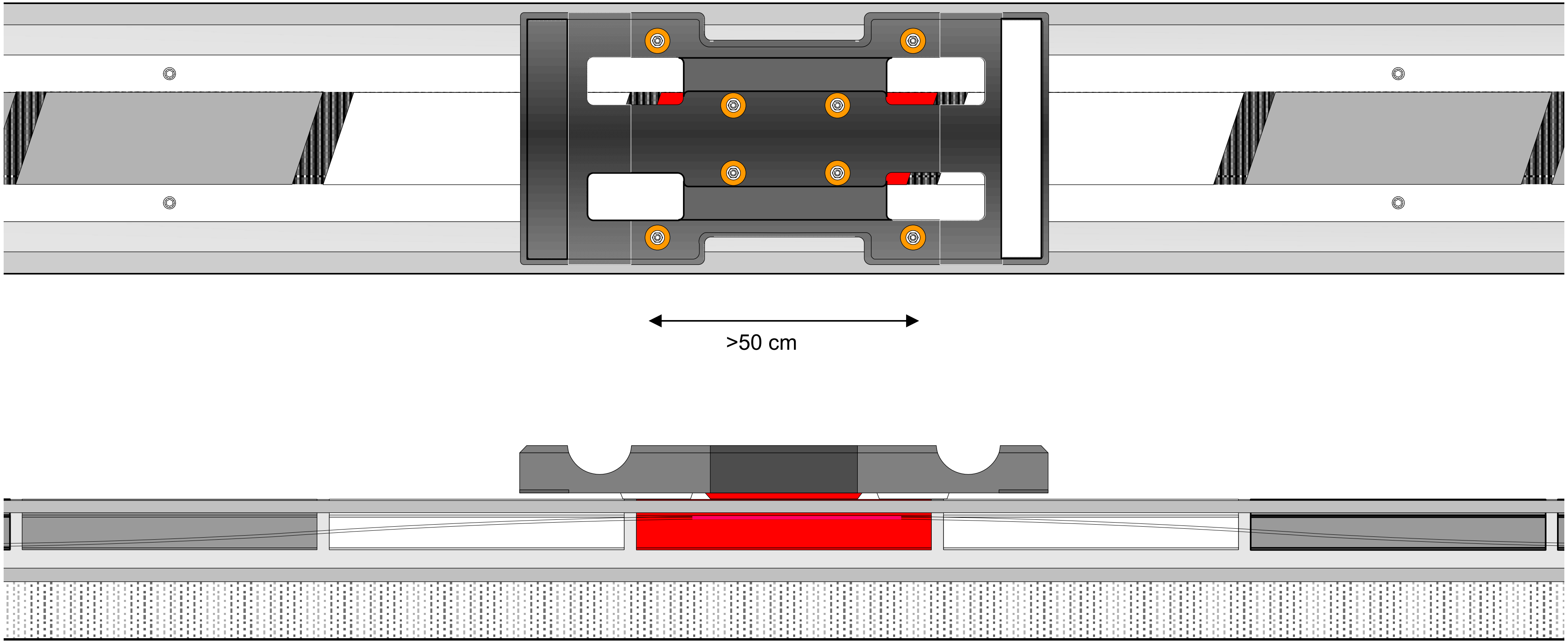
TramWave

Top view of operation

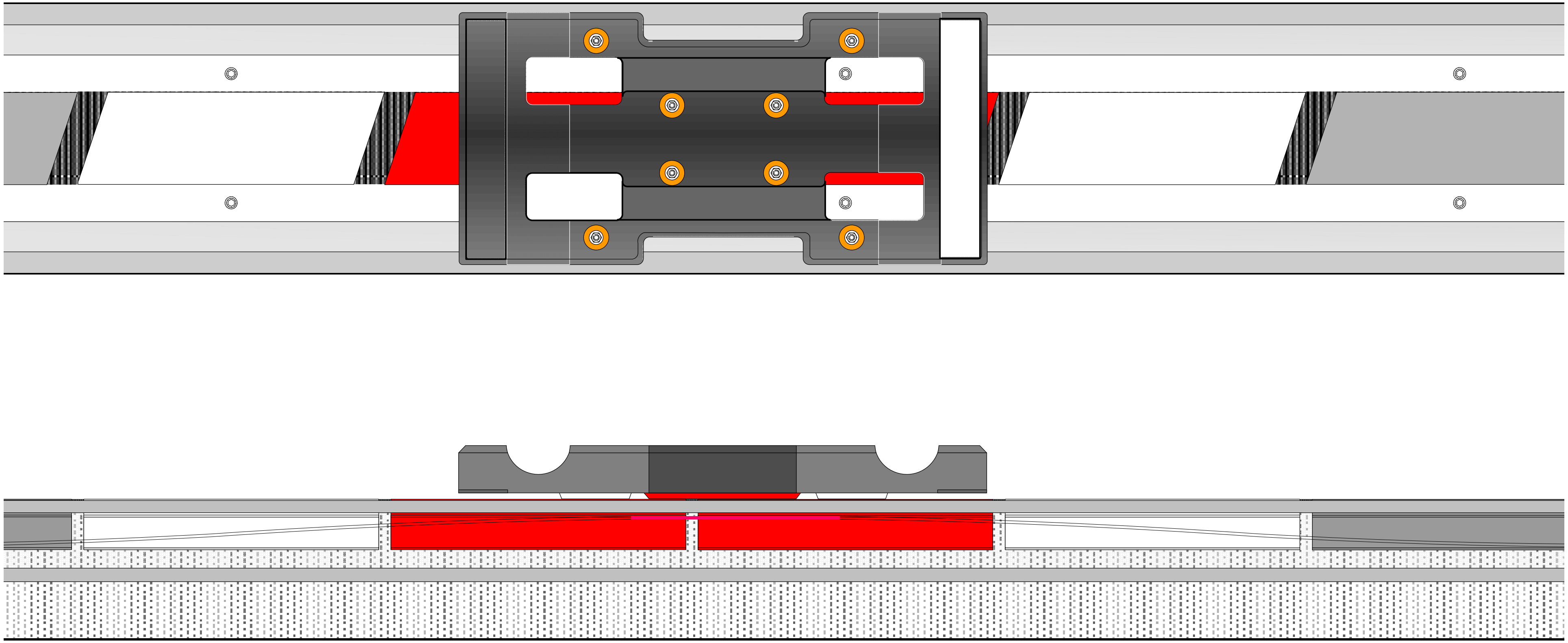
TramWave



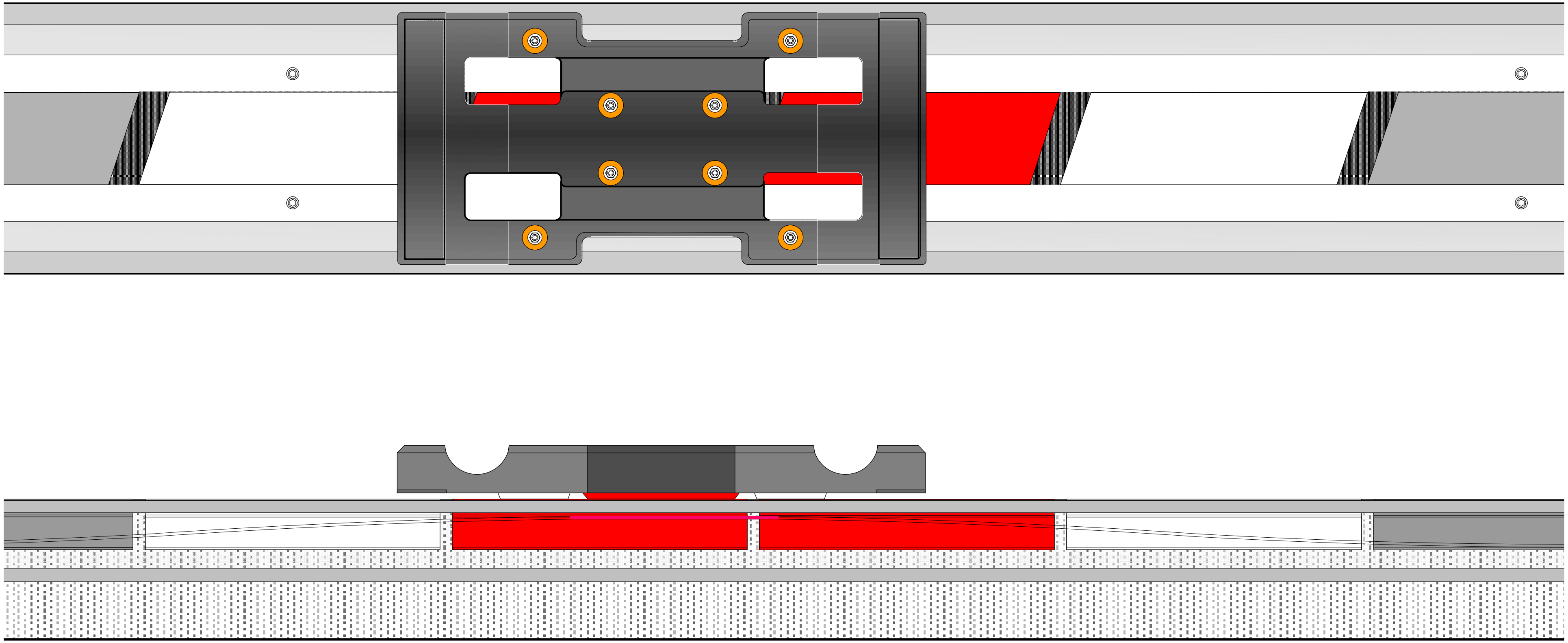
TramWave



TramWave



TramWave



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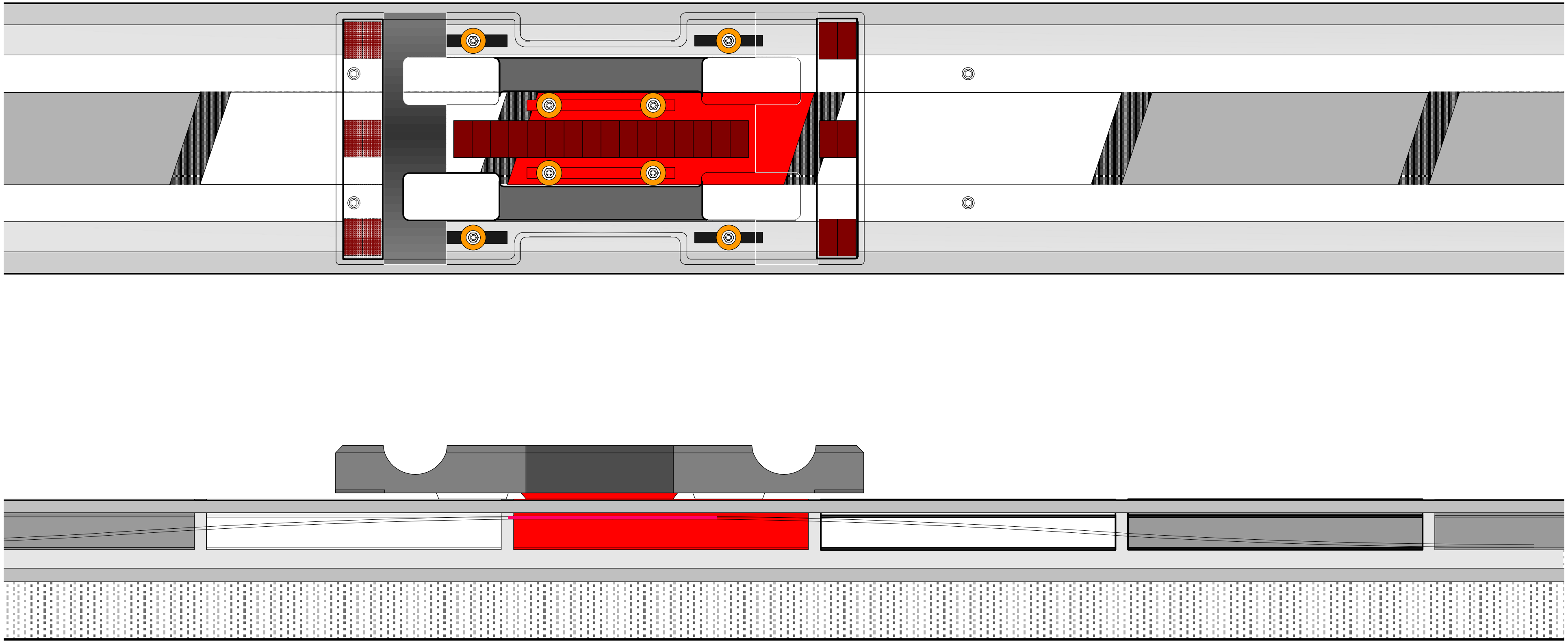

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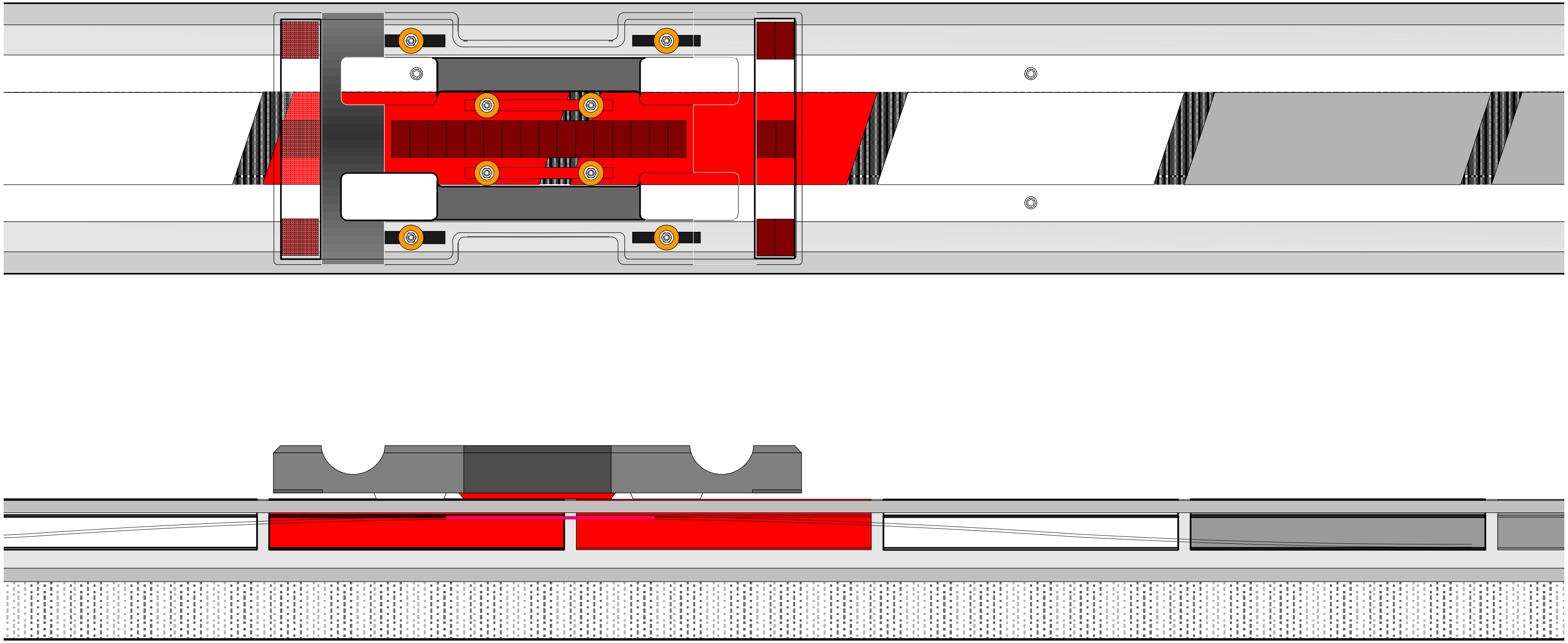
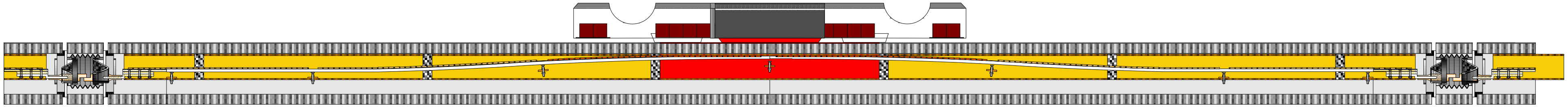


TramWave

More details of operation

TramWave



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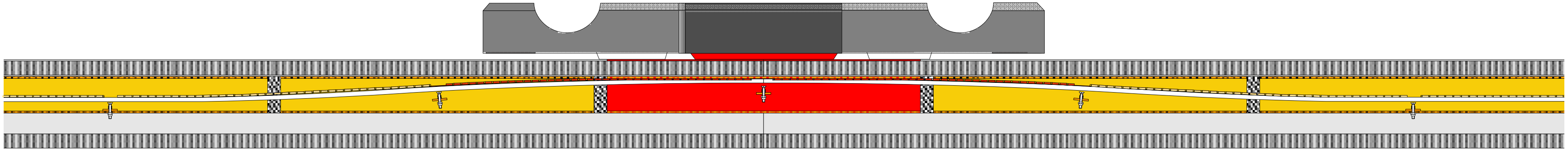
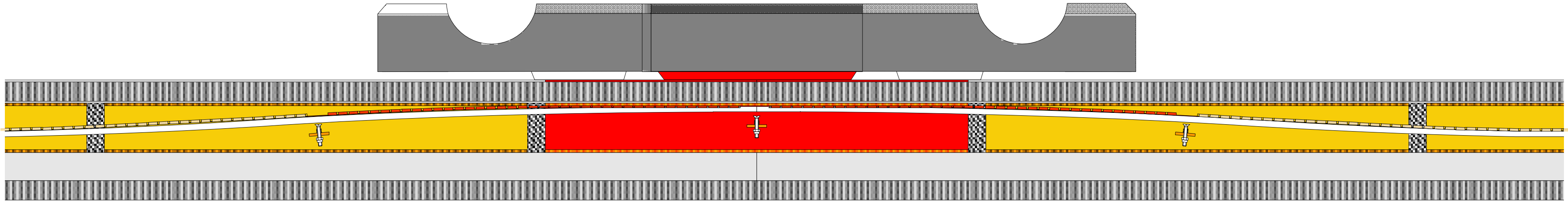


TramWave



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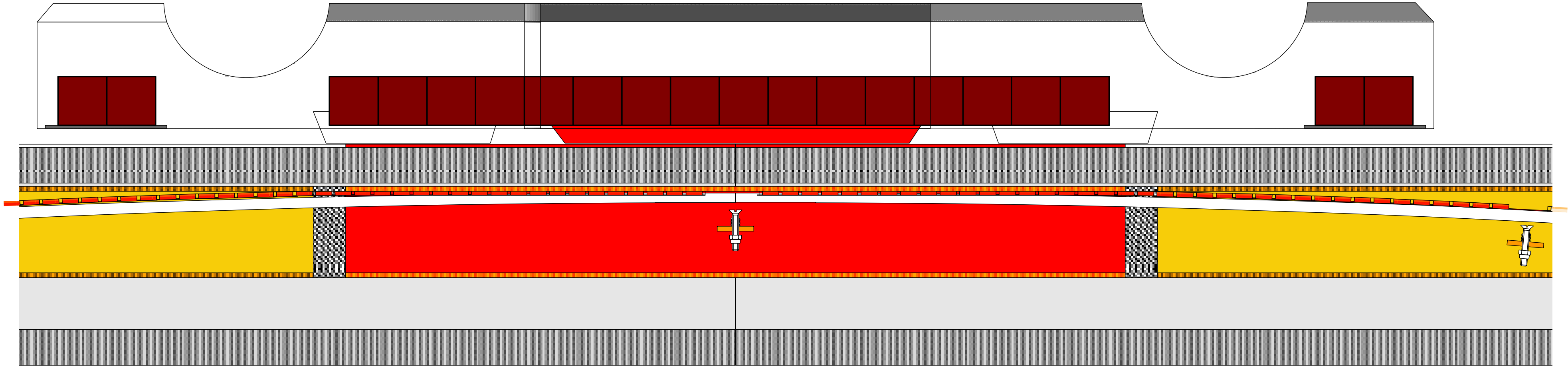

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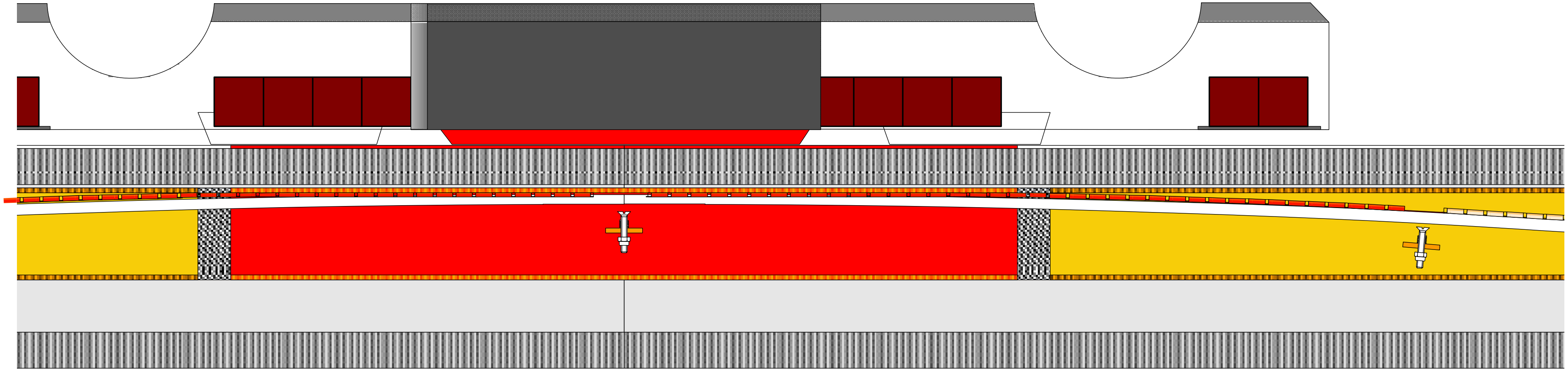

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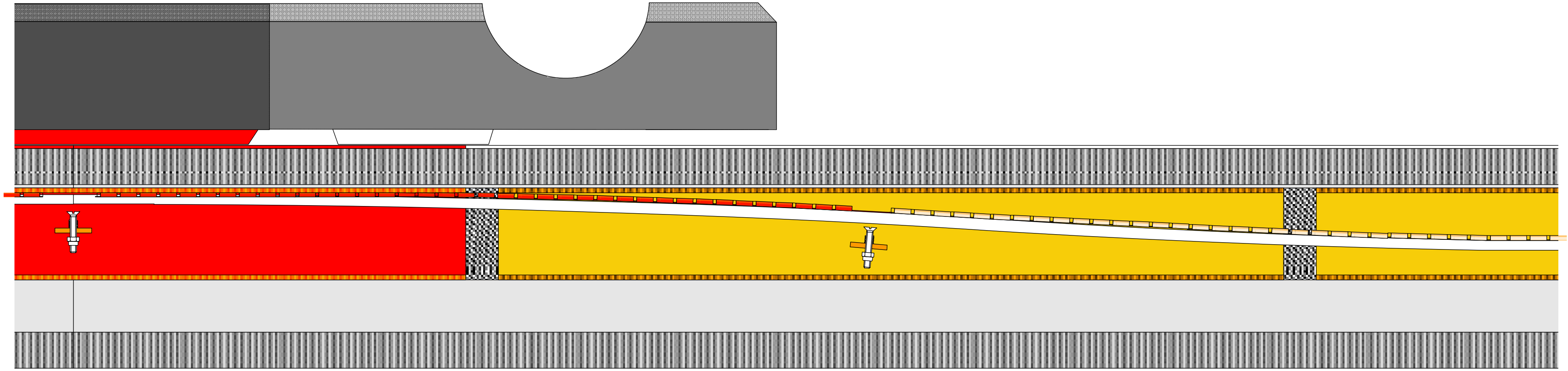
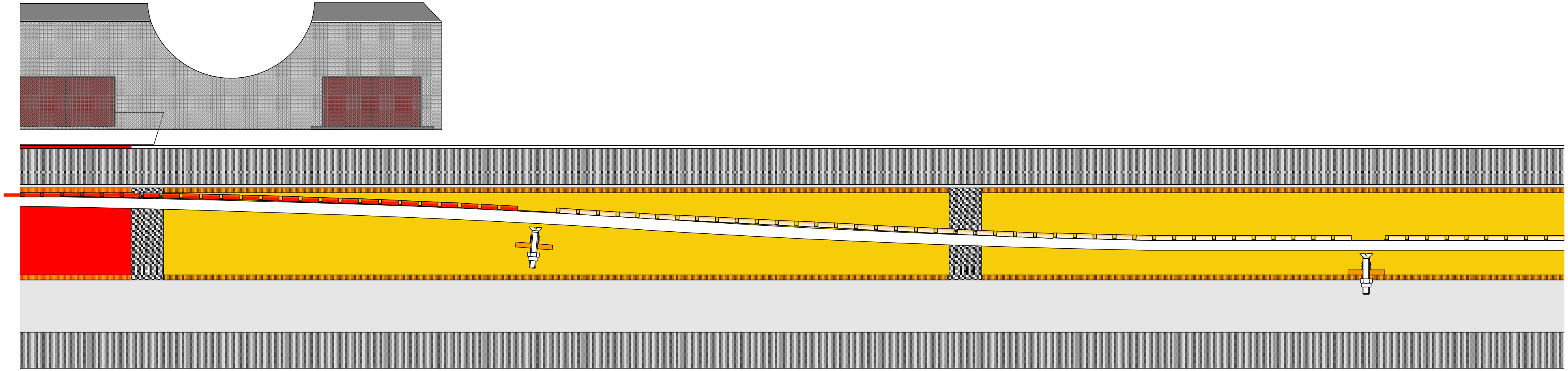
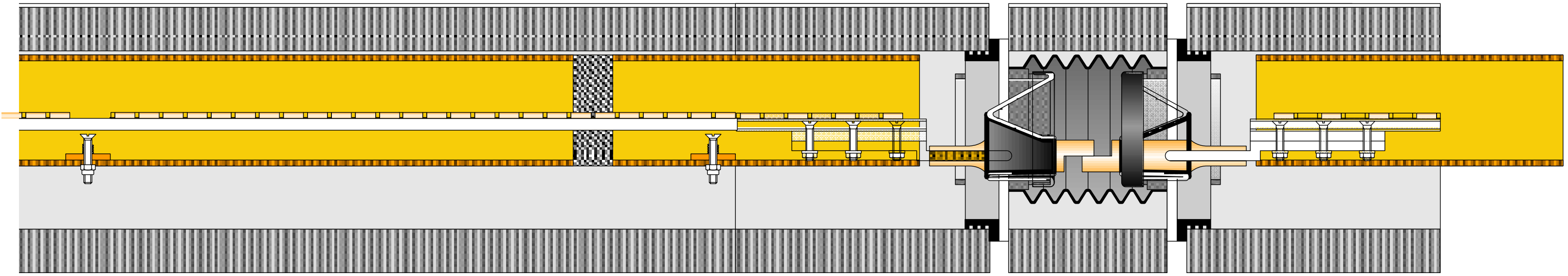


TramWave



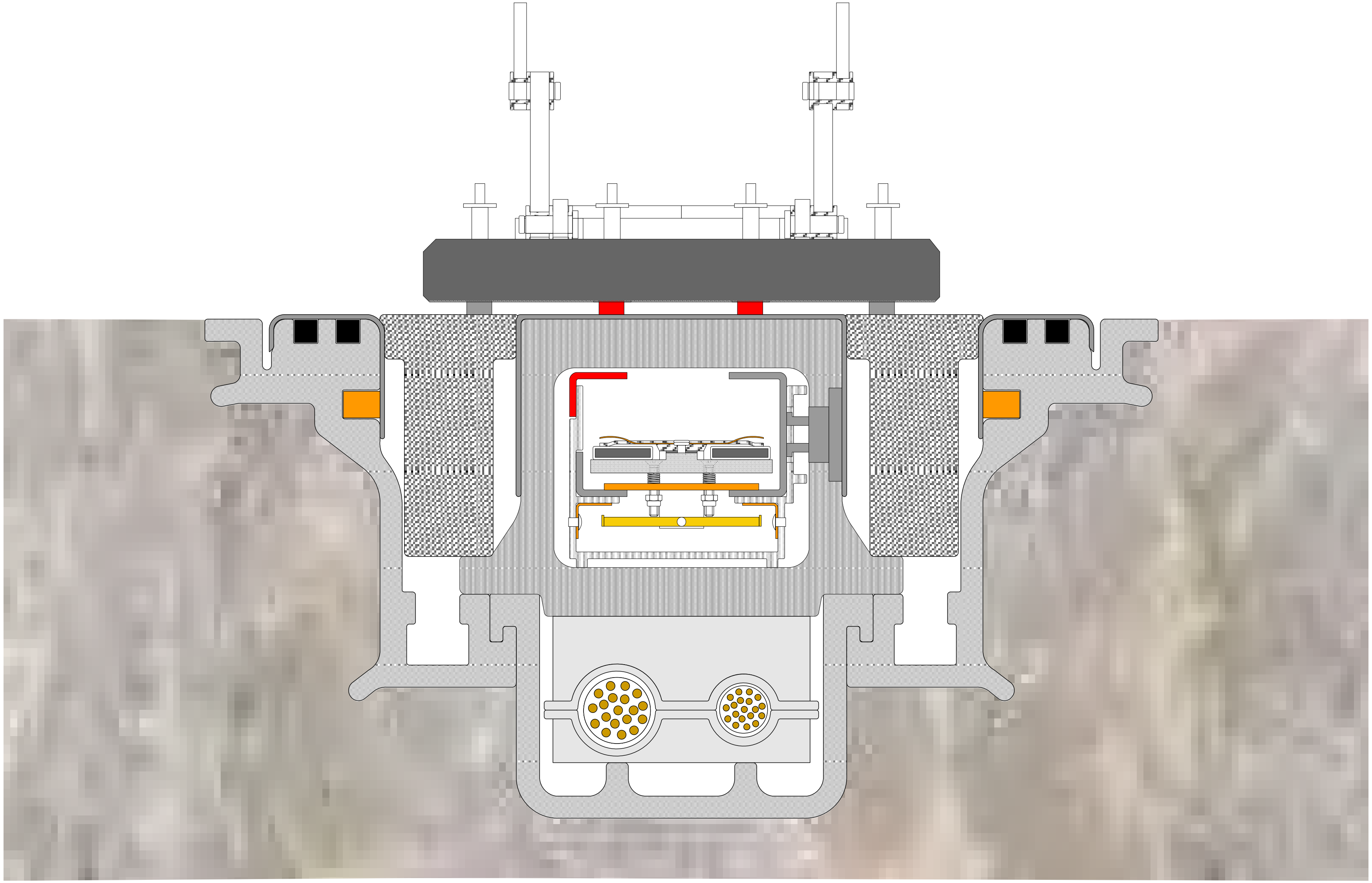
TramWave



TramWave

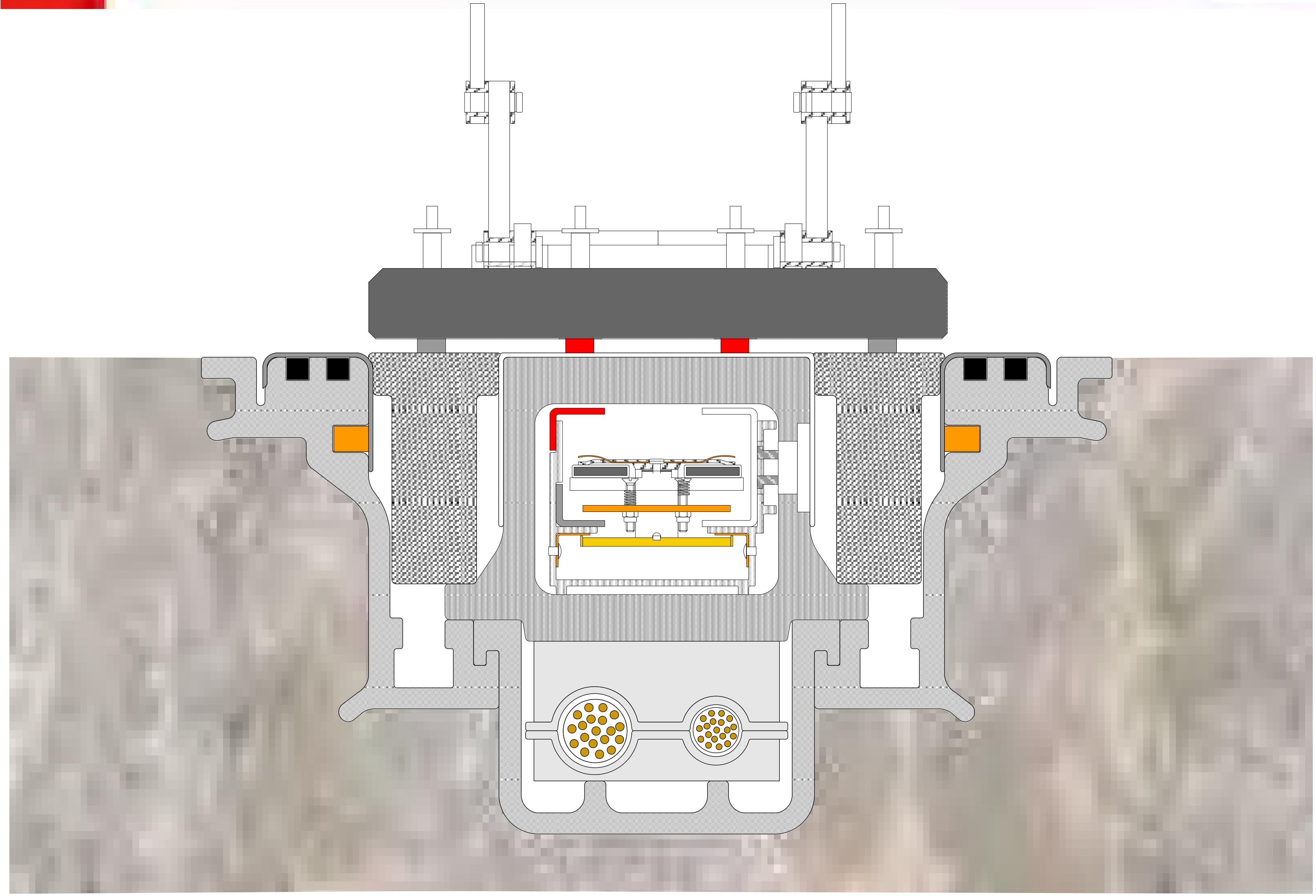
A full line section: view of operation

TramWave



AnsaldoSTS
A Finmeccanica Company

TramWave



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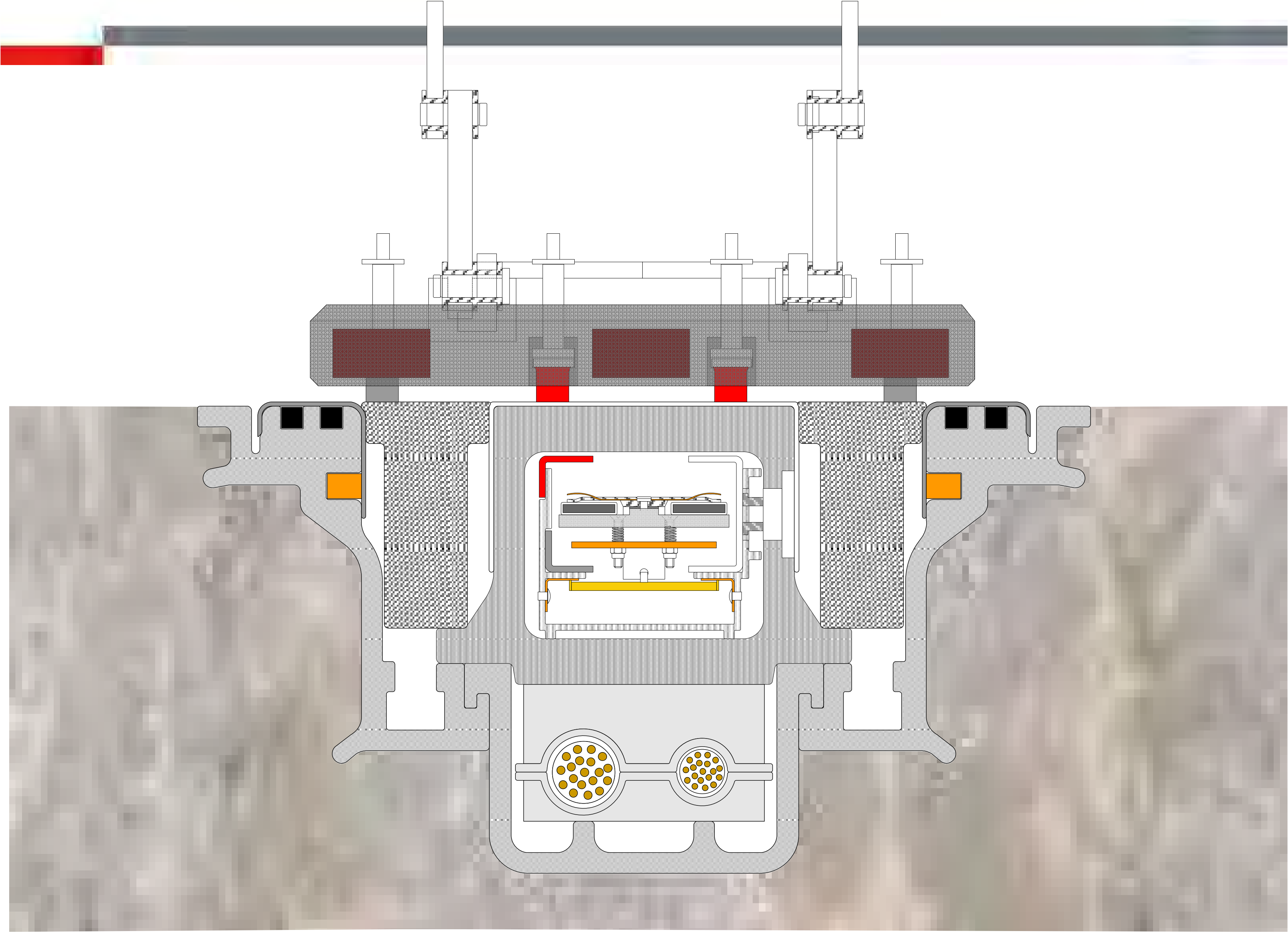

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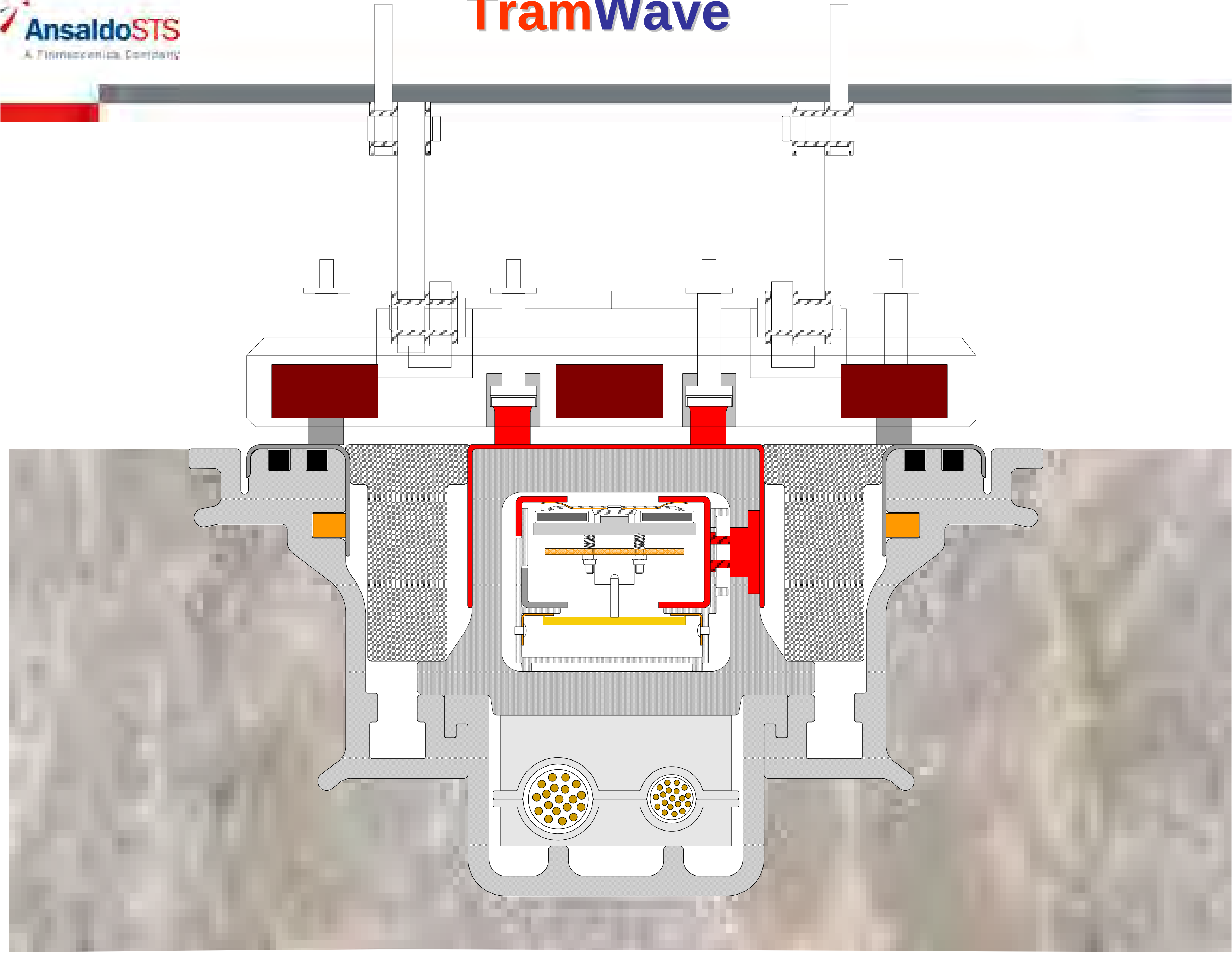

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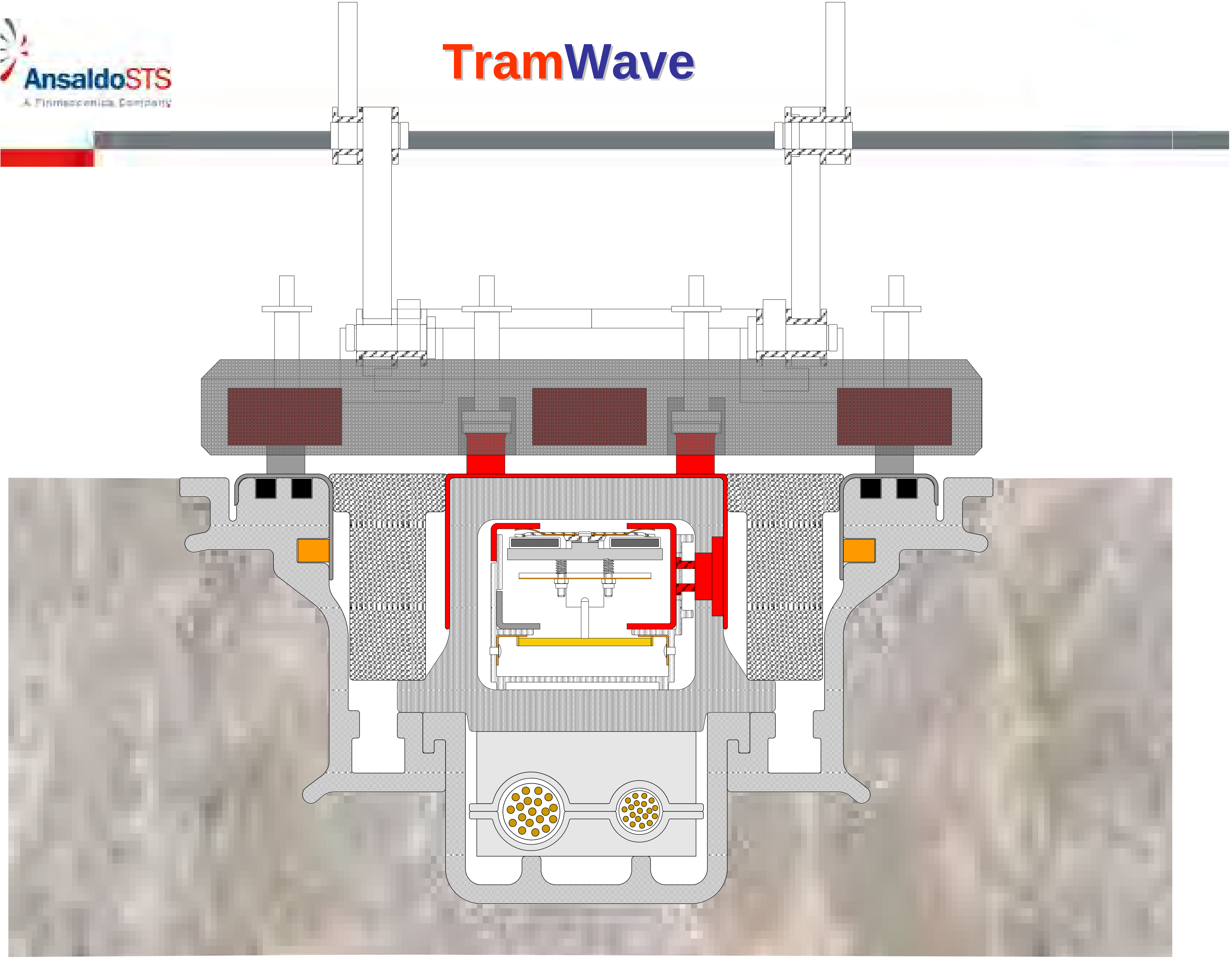

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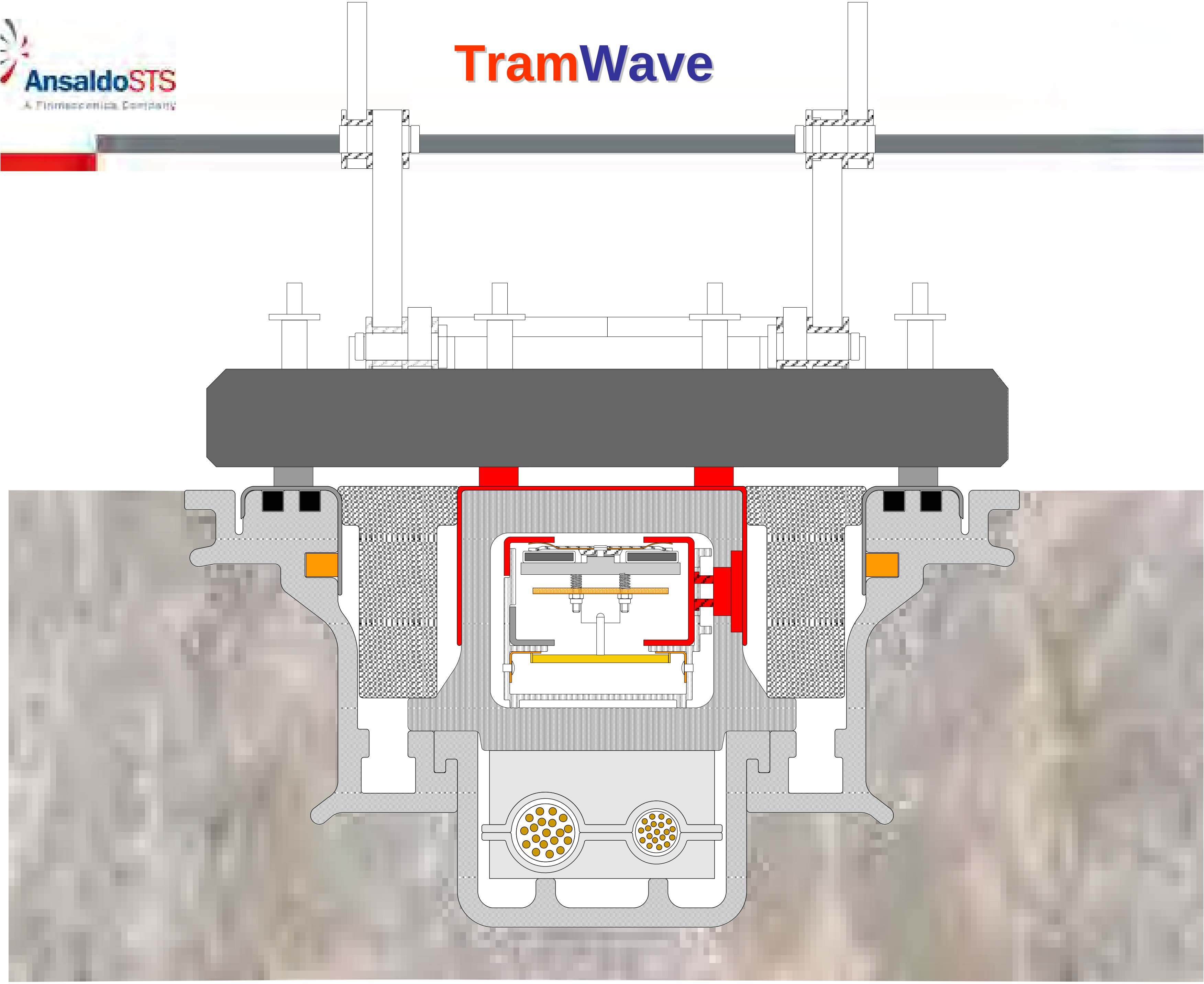
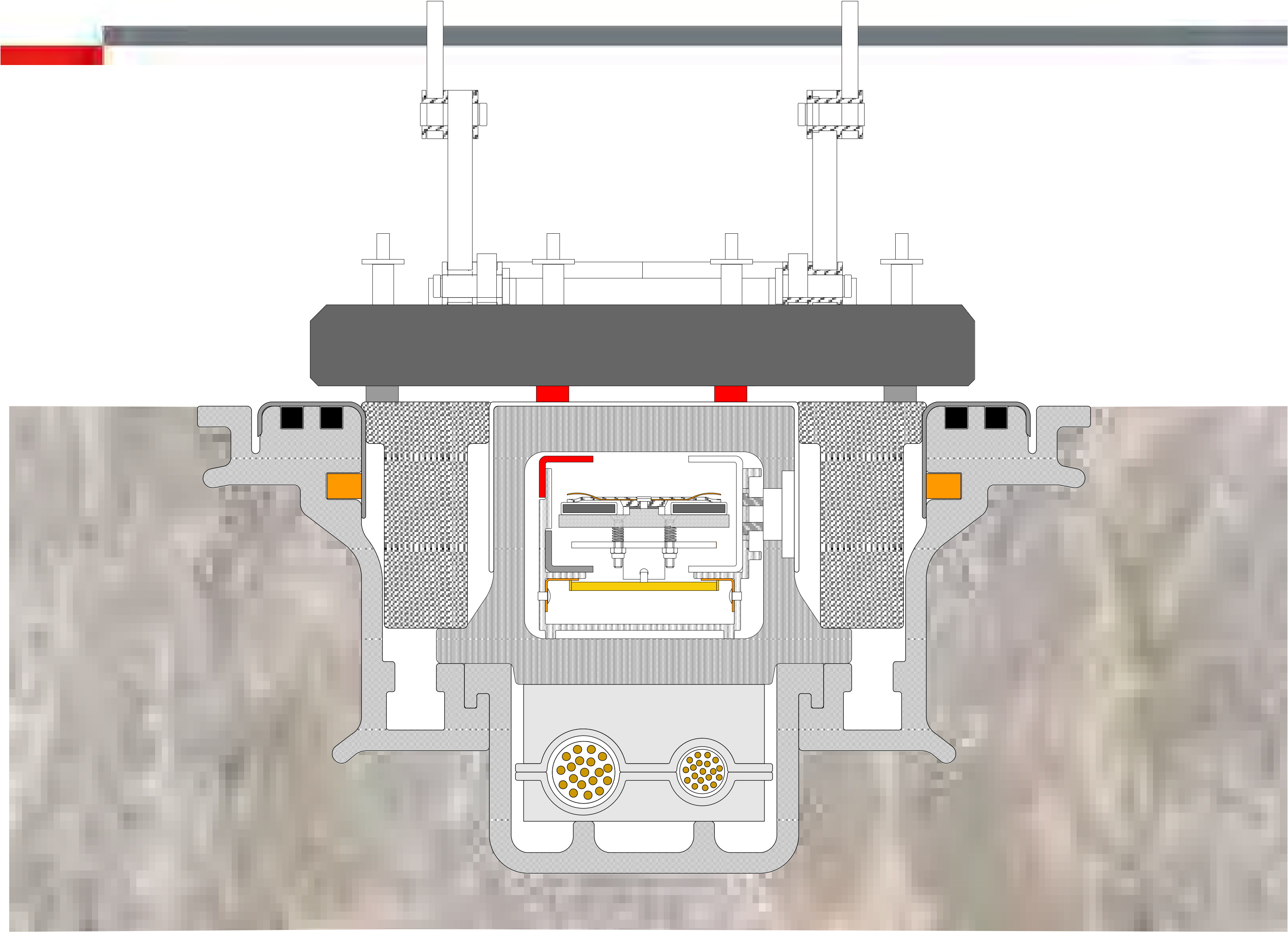


AnsaldoSTS
A Finmeccanica Company

TramWave



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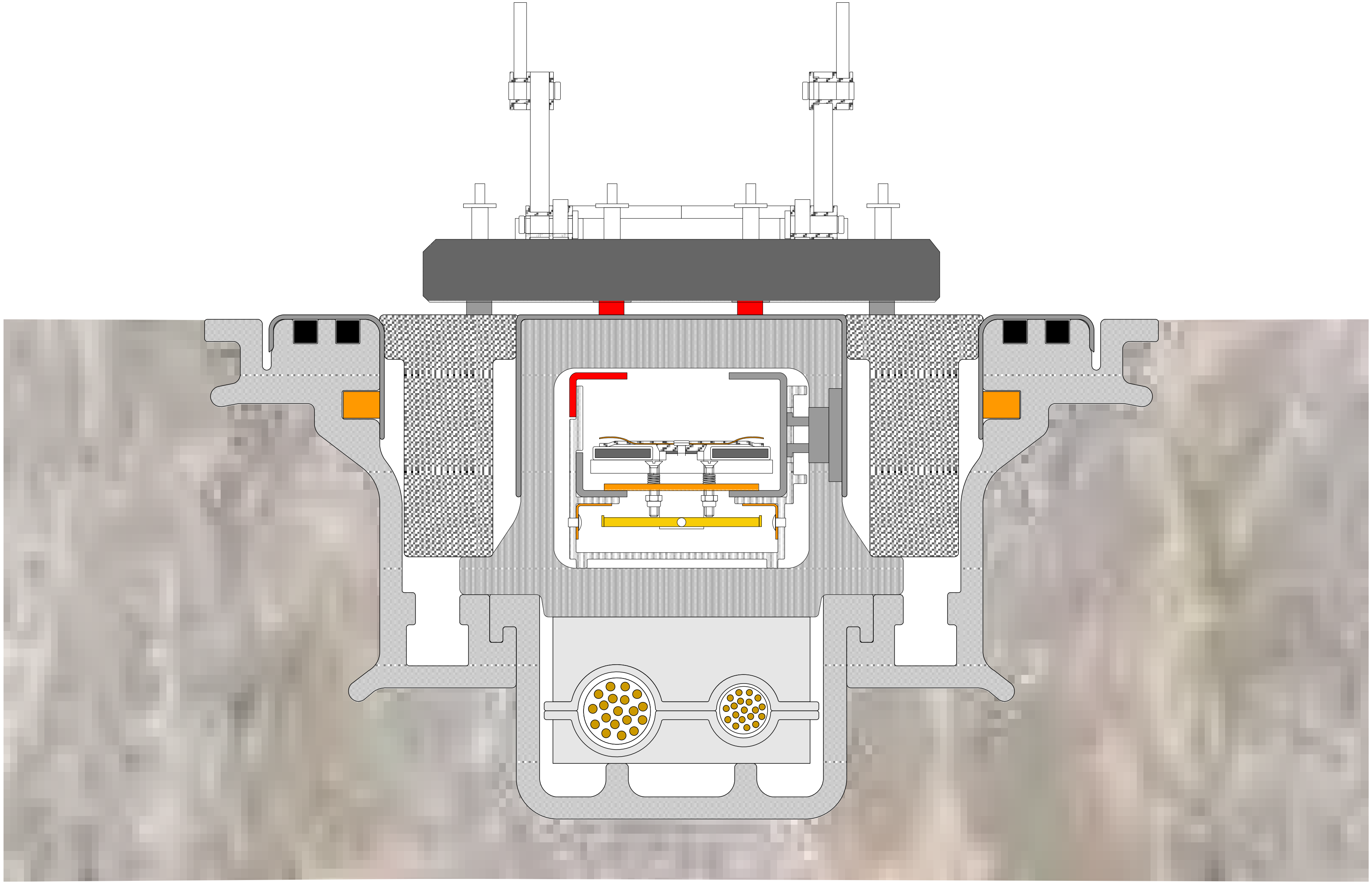
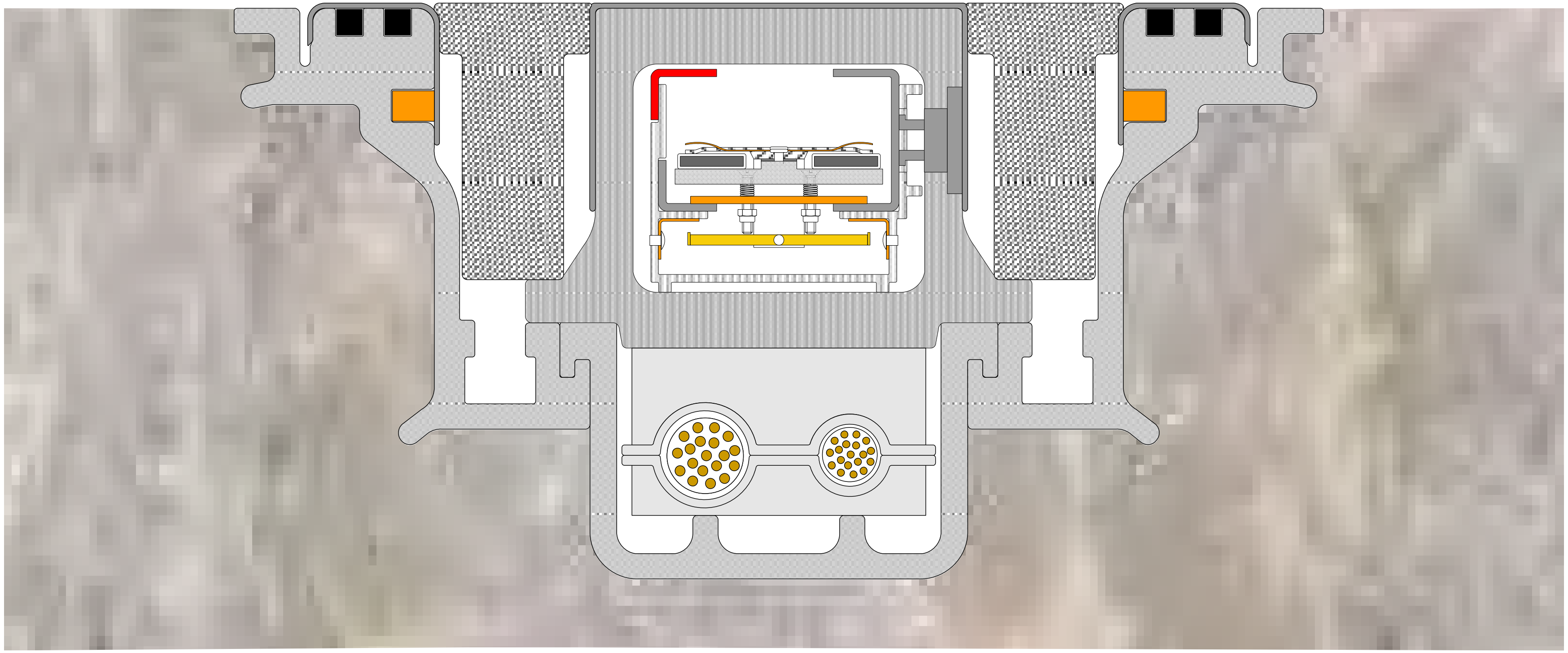


TramWave

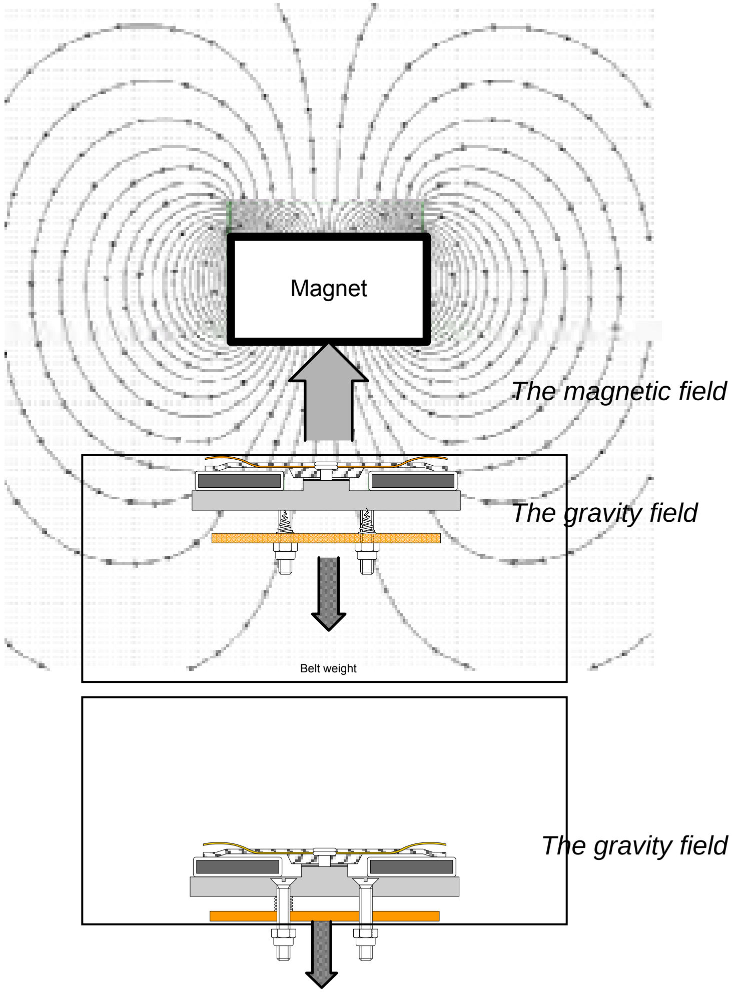


TramWave

Main Safety Issues

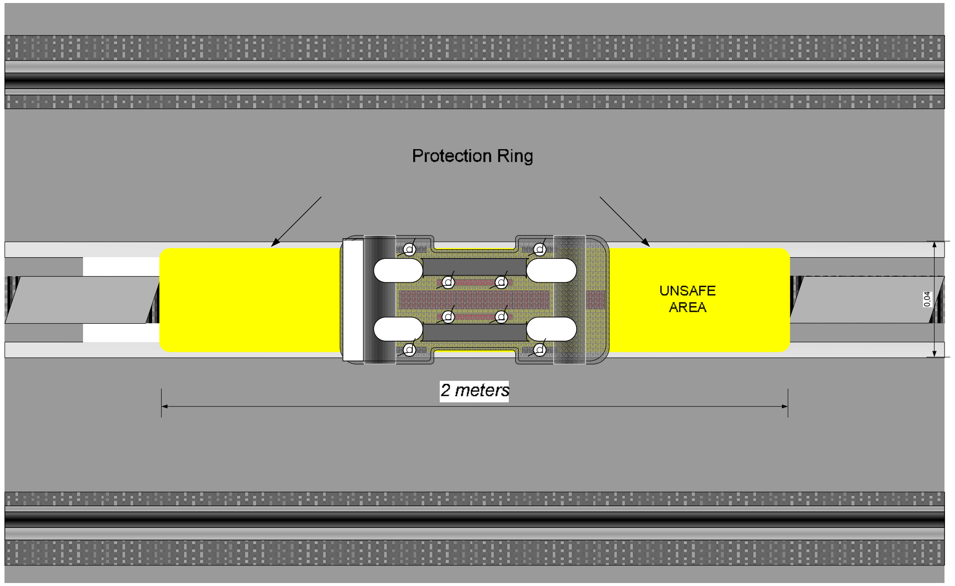
TramWave

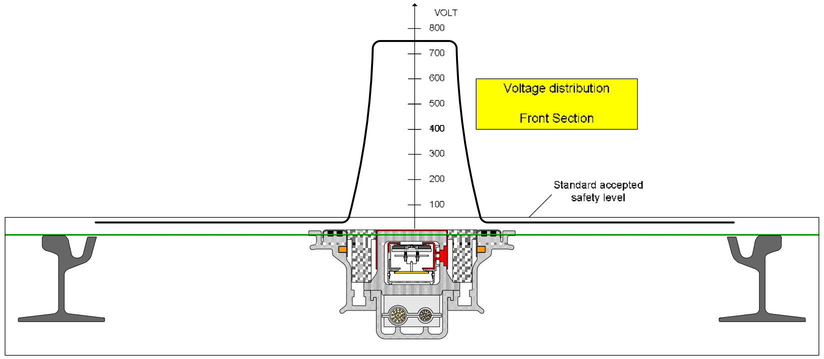
- The concept and the implementation of the safety requirements ensure the safety of the system in any normal operational condition as well as in any possible fault condition or accident.
  - The system goes “naturally” in the condition of safety
  - The absence or incorrect position of magnetic power collector over the line causes the drop of the flexible belt to the rest condition, connecting all the segment involved to the negative.

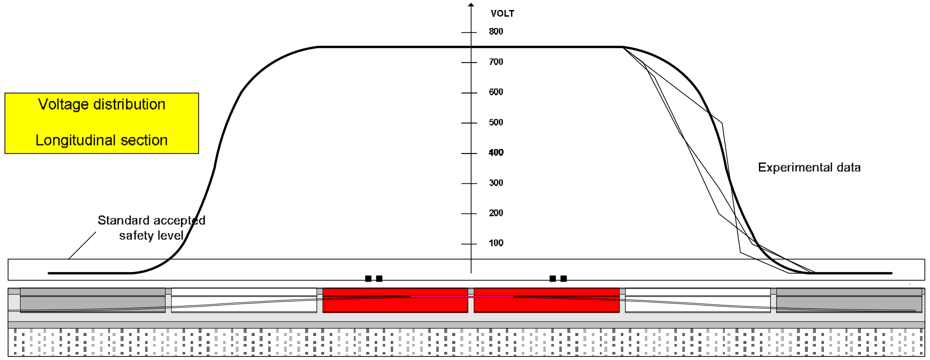


TramWave

- The activated part of the line is always enclosed by elements connected to the negative.
  - These element act as a “Virtual Protection ring”
  - The protection ring follows the power collector .
  - Safety is always assured even is case of water puddles .
  - The running rails act as a second barrier
- The voltage level all around the activated parts remains in any condition lower than the standard requirements.

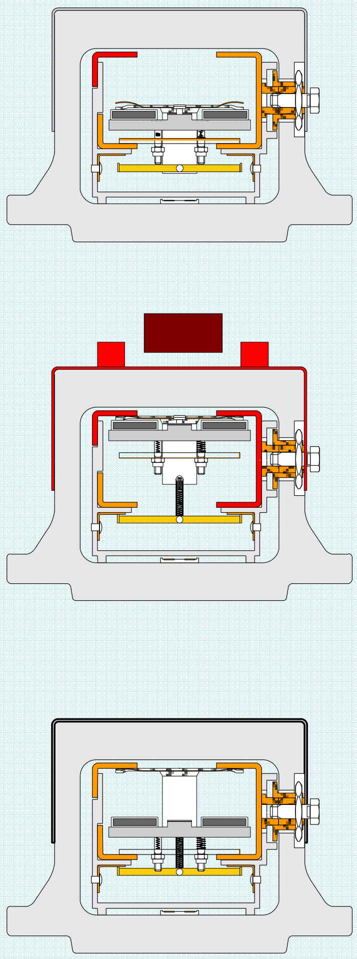




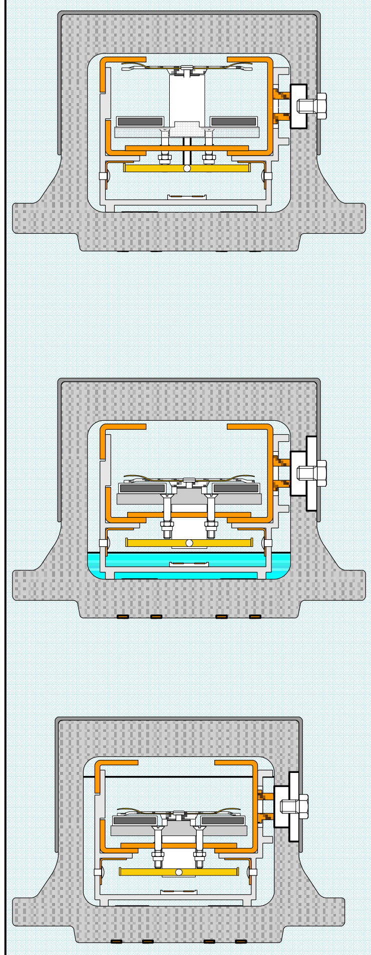


TramWave

- The design and the realization of the flexible belt and the safety negative concept assures the safety condition in the most severe conceivable accident conditions.
  - The “stick” of a positive contact
  - Loss of sealing and presence of a large quantity of water inside a single module.
- The diagnostic system allows a fast detection of the faulted module.

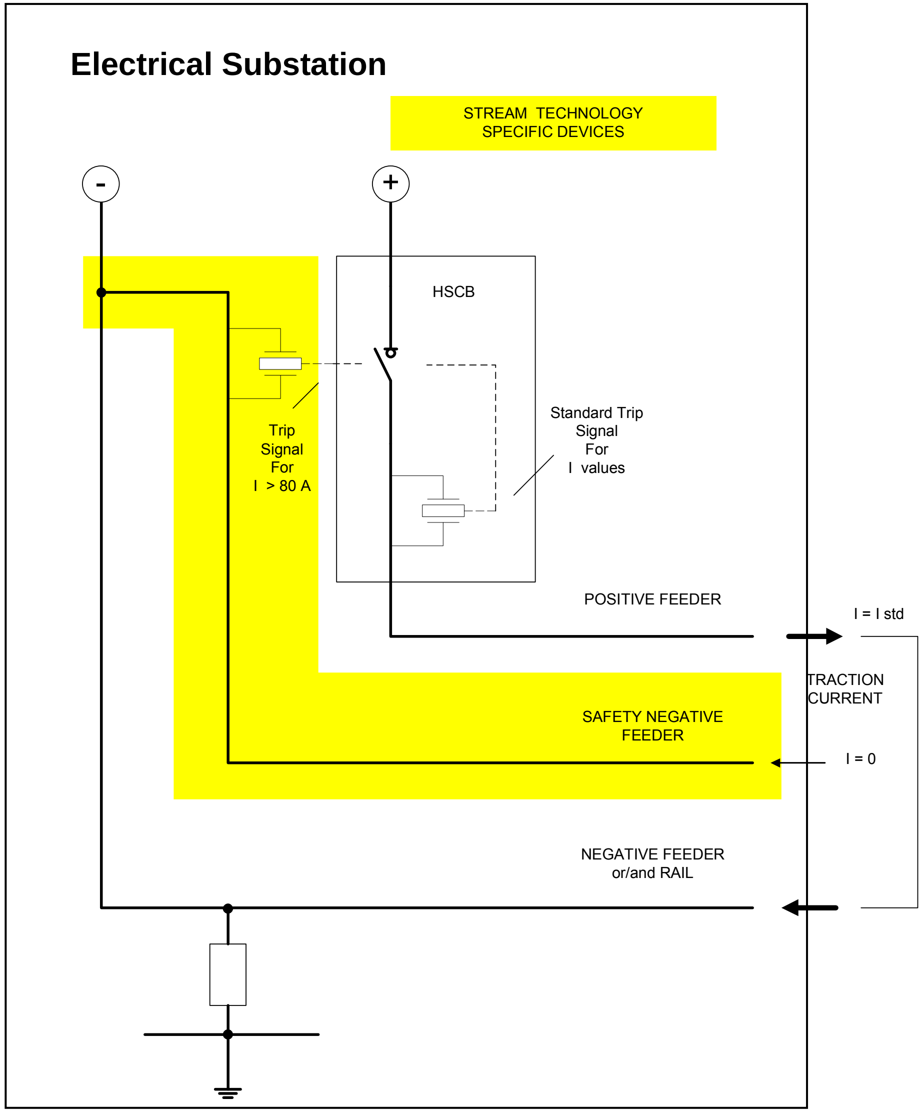


Contact Stick



Water inside the module

Electrical Substation



STREAM TECHNOLOGY
SPECIFIC DEVICES

-

+

HSCB

Trip
Signal
For
I > 80 A

Standard Trip
Signal
For
I values

POSITIVE FEEDER

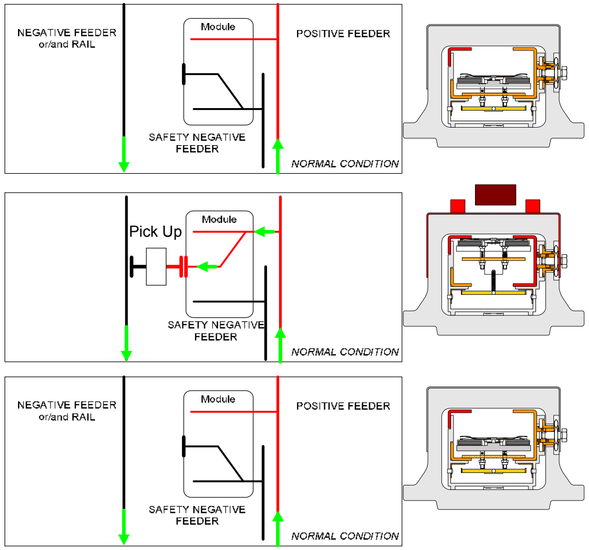
I = I std

TRACTION
CURRENT

SAFETY NEGATIVE
FEEDER

I = 0

NEGATIVE FEEDER
or/and RAIL



NEGATIVE FEEDER
or/and RAIL

Module

POSITIVE FEEDER

SAFETY NEGATIVE
FEEDER

NORMAL CONDITION

Pick Up

Module

SAFETY NEGATIVE
FEEDER

NORMAL CONDITION

NEGATIVE FEEDER
or/and RAIL

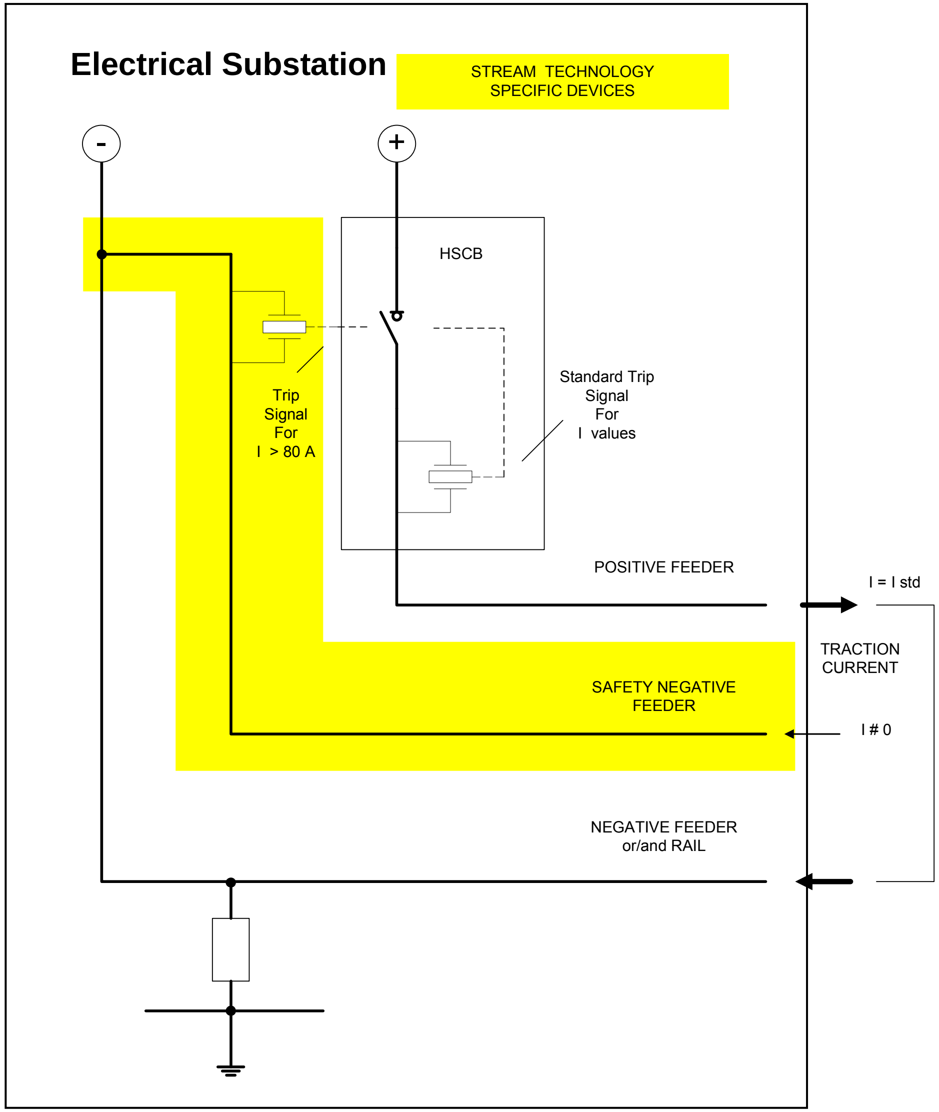
Module

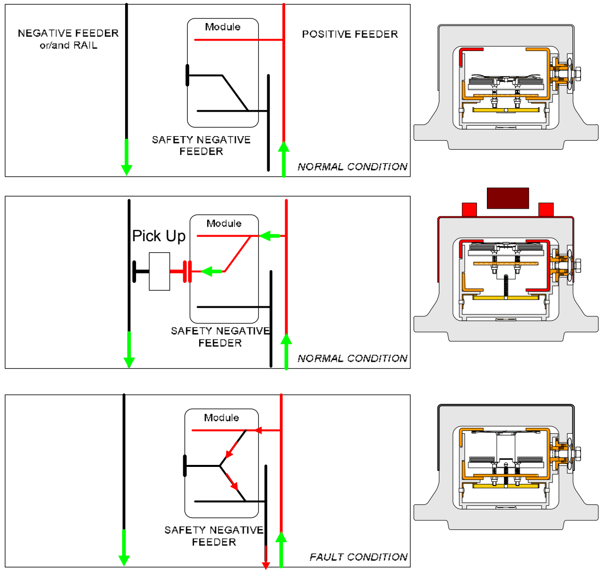
POSITIVE FEEDER

SAFETY NEGATIVE
FEEDER

NORMAL CONDITION

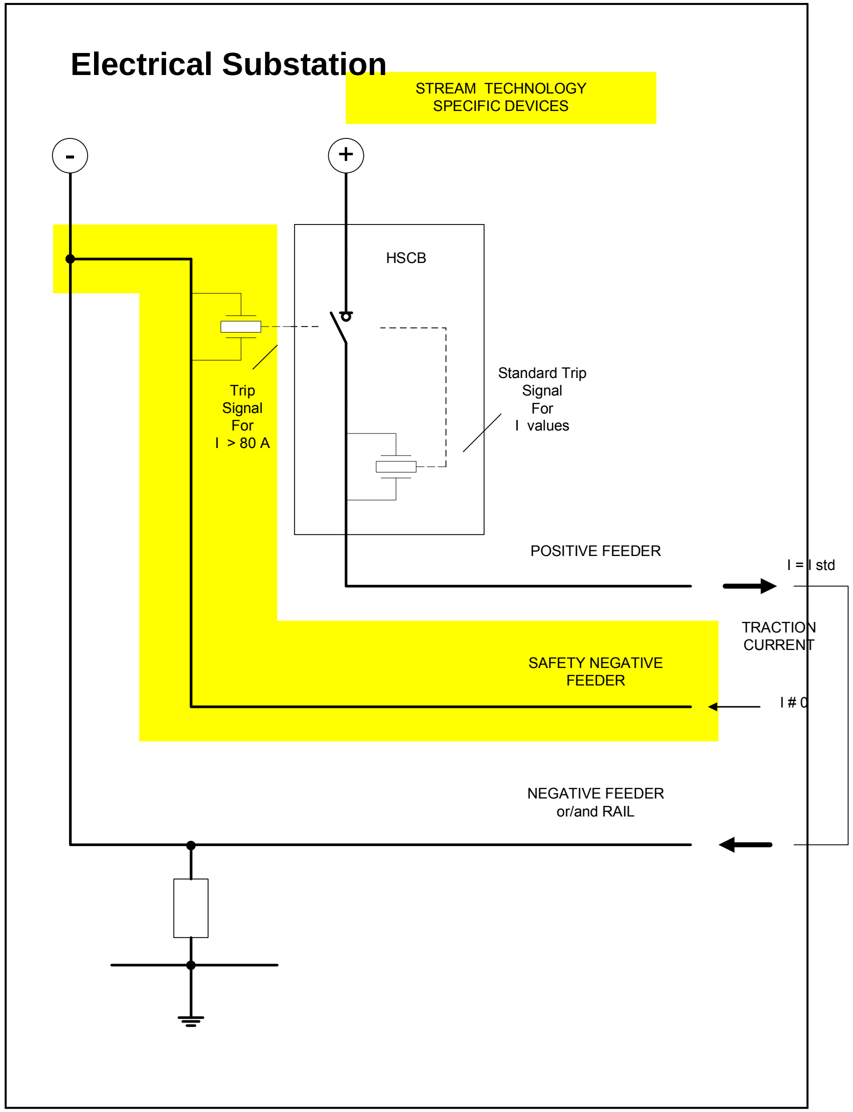
TramWave

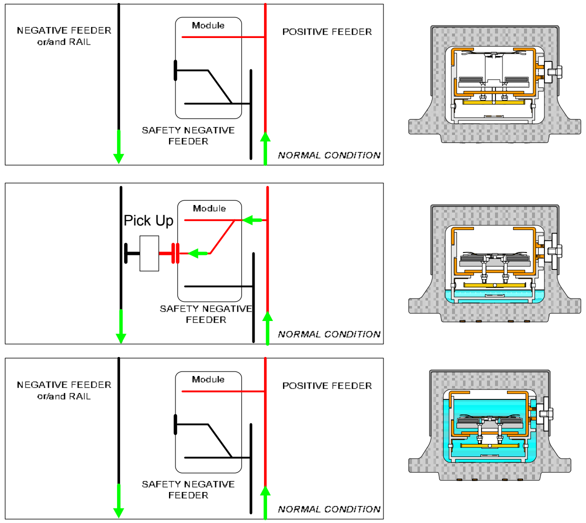




Event: Contact Stick to positive

TramWave





Event: water inside the module

TramWave

MAIN PERFORMANCE HIGHLIGHTS

- The technology can be used different type of rail vehicles in a wide range of power
- The system allows to cut many concern about stray currents, saving related installation and maintenance costs
- The technology can be used without any modification for a multi-modal use.
  - The power line could shared with rubber tyred electric vehicles
- The system could take profit and be integrated with energy storage on board.
  - Management of particular situation or singularities
  - Emergency situations
  - Fast recharge area (static or dynamic).
- The integrated diagnostic allows:
  - A fast identification of the module that presents operational disturbance (even transitory for an early warning)
  - Localizing the vehicle on the line
  - A useful support for operation and maintenance.

TramWave

- The maintenance level could be equal or better than a conventional overhead catenary.
- Any fault or operational problem remains confined in the affected module
- The maintenance activities consists in the change of the module:
  - 30 minutes is the mean time on site to change a module
  - Few persons could complete the operation without special or heavy tools.
  - The maintenance could be postponed at the end of the day.

TramWave

Thank you for your attention

Bovenleidingsloze tractie

Techniek ten dienste van duurzaamheid en behoud van het historisch karakter van stadscentra

KVIV Spoortechnieken

Yves Carels

17 February 2011

TRANSPORT

ALSTOM

Agenda

1. Why wireless trams ?
2. Wireless systems in operation & projects
3. How does APS work ?
4. APS evolutions

Why wireless trams?

To preserve urban environment

Why wireless trams?

To share restricted space in urban environment - no catenary posts

Why wireless trams?

To facilitate access in narrow streets
– fire brigade, facade renovation, …

Why wireless trams?

To preserve nature in cities

Agenda

1. Why wireless trams ?
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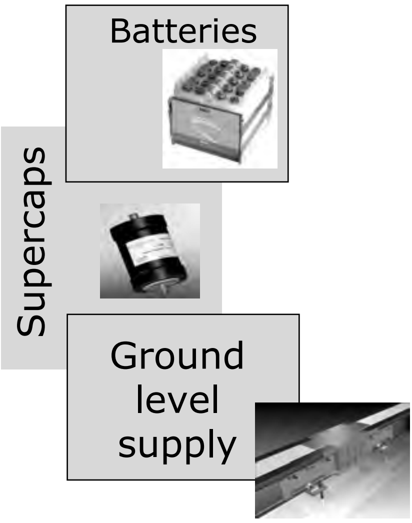
3. How does APS work ?
4. APS evolutions

Tram without catenary : Overview



	One tram in passenger service	Line(s) in passenger service
• Alstom Nice		☺
• Kawasaki Swimo		
• Siemens HES		
• Alstom STEEM	☺	
• CAF ACR	☺	
• Bombardier Primove		
• Ansaldobreda Tramwave		
• Alstom APS		☺

Tram without catenary : Batteries

- Tramway service in Nice city since 2007
- Two 450m sections run at 30 km/h without catenary
- NiMH battery technology, with slow recharge under catenary sections : guaranteed lifetime 5 years at 25℃ operation temperature
- Battery box internal temperature regulated @ 25℃
- Return on experience on all operating scenarii, battery & tram handling, etc
- 30m tramway solution, extendable to 40m

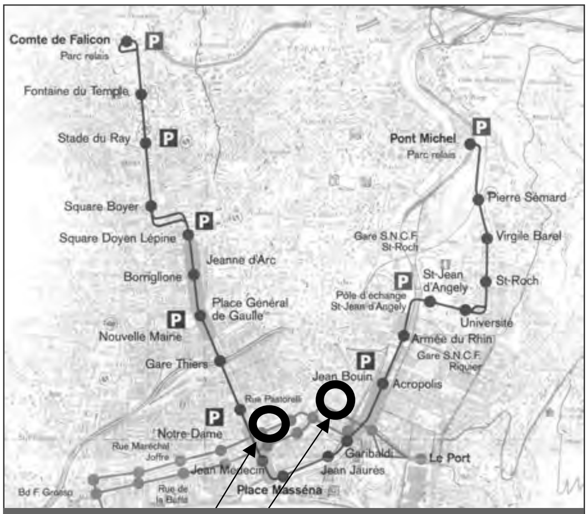
Wireless solutions: a full service proven range

APS and batteries available for optimal, specific adaptation to local needs

1. Short wireless sections: Nice

Batteries

- NiMH-Batteries
- The solution for short wireless sections
- Acceleration and max. speed adapted to city centre

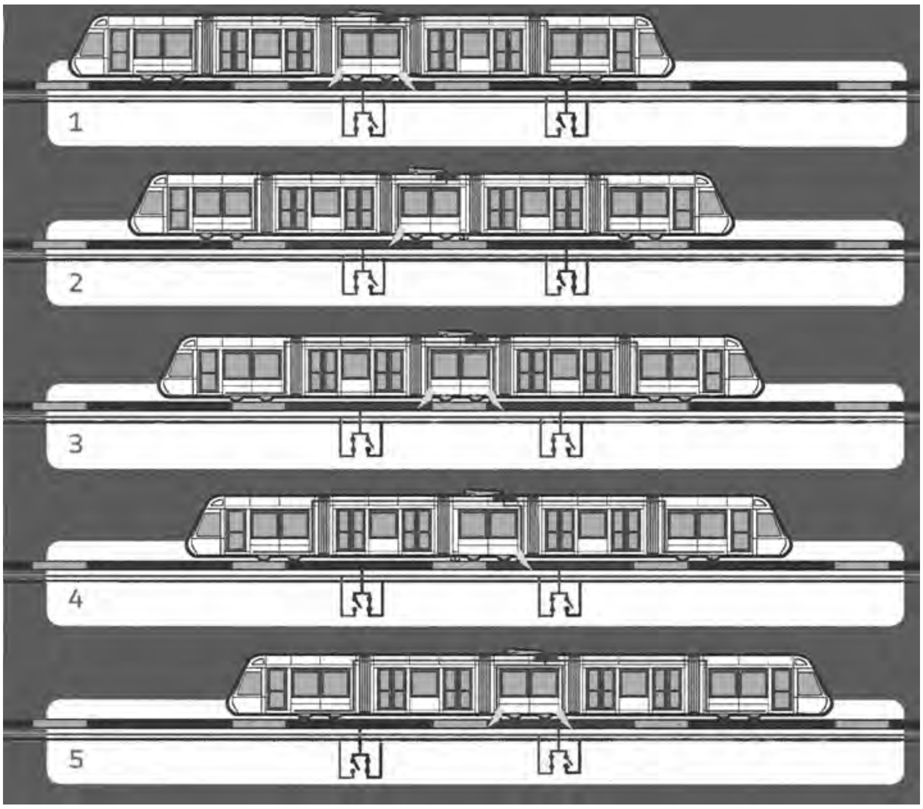


- Commercial service in 2007
- No overhead wires on 2 squares
  - *Place Masséna: ~435 m*
  - *Place Garibaldi: ~485 m*

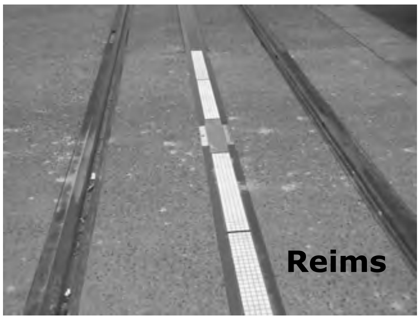
Tram without catenary : APS

Alimentation par le Sol

Ground-level Power Supply



Tram without catenary : APS



- Proven solution : Bordeaux network in passenger service (13.4 km)
- Return on experience and extensive product improvement process
- No power restriction - full speed and acceleration, possibility to use continuously reinforced HVAC for hot climate
- No risk of “empty tank”
- Complete intrinsic safety
- Customer confidence :
  - –contracts in 2006 for Reims / Orléans / Angers,
  - –followed by Dubai / Brasilia (hot climate version)
  - –recently signed (Sept ’10) in Tours

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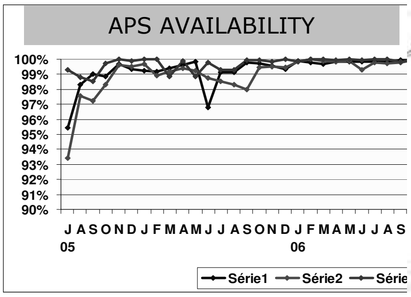
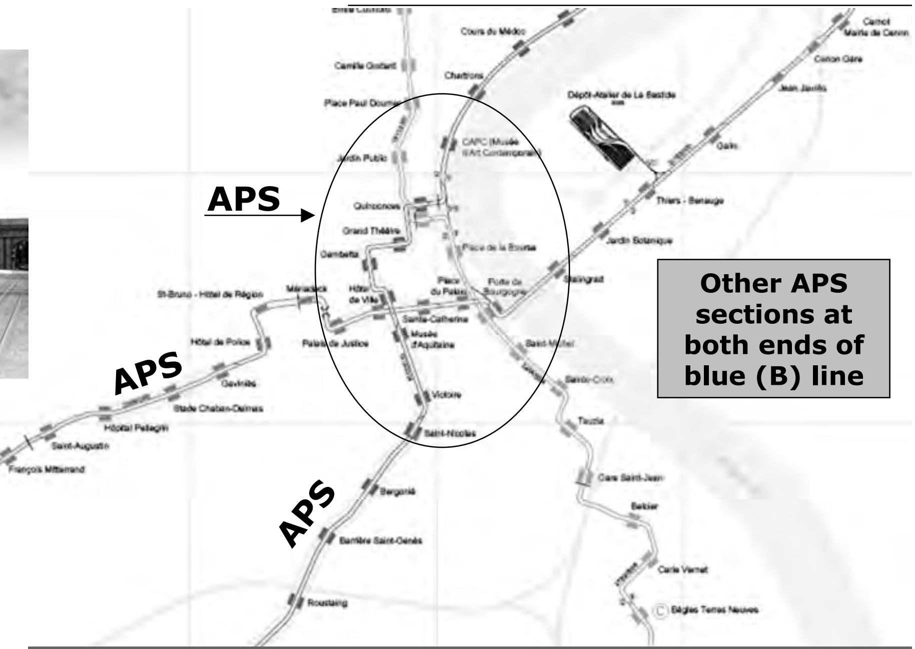
Tram without catenary : APS Bordeaux





Other APS sections at both ends of blue (B) line

- 3 Lines in service (2004): 24,3 km with 10,85 km twin-track APS
- Second phase (end 2007) : 19,6 km incl. 2.2 km APS
- Final Network : 43.9 km with 13,4 km twin-track APS

Reims

- New LRT line 10 km in 30 years concession
- Alstom scope: 18 Citadis, APS, infrastructure, system
- APS scope: Design, Supply, Installation and Testing :
    - 3,92 km of APS single track
    - 9 APS Turnouts
    - 18 on board Equipement

- Project start in July 2006
- APS install start in June 2009 (compl. June 2010)
- APS T&C start in July 2010 (compl. August 2010)
- PTO : 18/04/2011 (1 year warranty)
- Testing in progress and successful

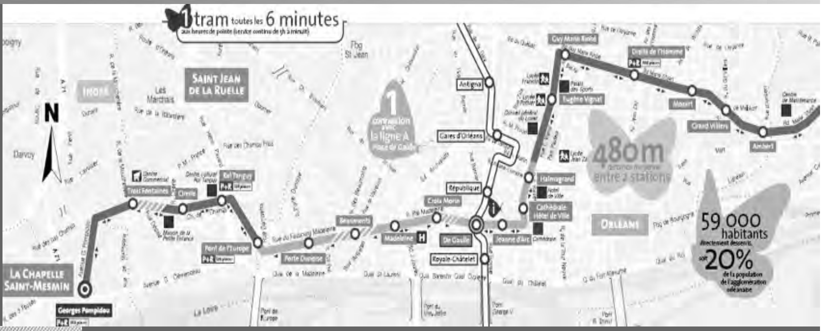
Angers

- New LRT line 12 km
- Alstom scope : APS and 17 Citadis
- APS scope: Design, Supply, Supervision of Installation and Testing :
    - 2,82 km of APS single track
    - 5 APS Turnouts
    - 17 on board Equipement
- Particularity – **8%** gradient

- Project start in November 2006
- APS install start (June 2009)
- APS T&C start in Nov 2010 (compl. June 2011)
- PTO: June 2011 (14 months warranty)

Orléans

- New LRT Line: line 2
- Alstom scope: 21 Citadis, APS, tracks, railway signalling, system
- APS scope: Design, Supply, Installation and Testing :
    - 4,2 km of APS single track
    - 6 APS Turnouts
    - 21 on board Equipement



- Project start in Sept 2006
- APS install start in Oct 2010 (compl. June 2011)
- APS T&C start in August 2011
- PTO : 30/06/2012 (12 months warranty)

Tours

- New LRT line : 21 tramways, 15 kms track, 30 stations
- Alstom scope: 21 Citadis, APS
- APS scope: Design, Supply, Installation and Testing :
    - 3,6 km of APS single track
    - 4 APS Turnouts
    - 21 on board Equipement

- Project start in September 2010
- APS install start in Nov 2011 (compl. nov 2012)
- APS T&C start in November 2012
- Forecasted PTO : 2013

Dubai

- New LRT line : 11 tramways, 10 kms track, 13 stations
- The first city in the Gulf region to be equipped with a tramway transit system
- Alstom scope: 11 Citadis, APS, infrastructure (track, SST, E&M), system
- APS scope: Design, Supply, Installation and Testing :
    - 18,96 km of APS single track
    - 41 APS Turnouts
    - 11 on board Equipement

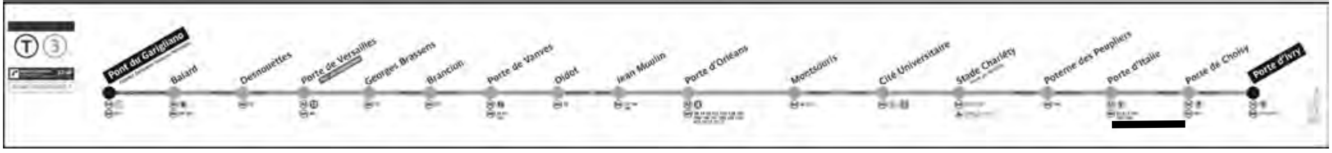
- Project start in June 2008
- 5 years warranty

Brasilia

- New LRT line : 39 tramways, 22 kms track, APS on 1,2 kms platform
- The first city in the Latin America to be equipped with a modern tramway system
- Alstom scope: 39 Citadis, APS, track on APS section,ticketing,signalling,OCC,system
- APS scope: Design, Supply, Installation and Testing :
    - 2,4 km of APS single track
    - 2 APS Turnouts
    - 39 on board Equipement

- Contract September 2009

Tram without catenary
On-board Solution : STEEM



- Recovery of braking energy
- Running without pantograph
- Tramway length 44 m, width 2.65m, 86 tons max @ 6P/m² i.e. 417 Passengers
- Supercapacitor solution
- Operation in passenger service including a 300m interstation wireless section

RATP INRETS PREDIT ADEME Agence de l'Environnement et de la Maîtrise de l'Energie

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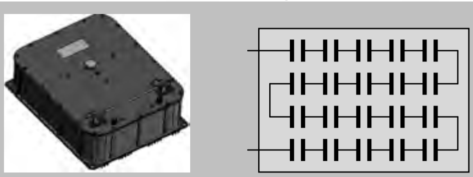
On-board Solution : STEEM

STEEM : Système Tramway à Efficacité Energétique Maximisée
Maximized Energy Efficient Tramway System

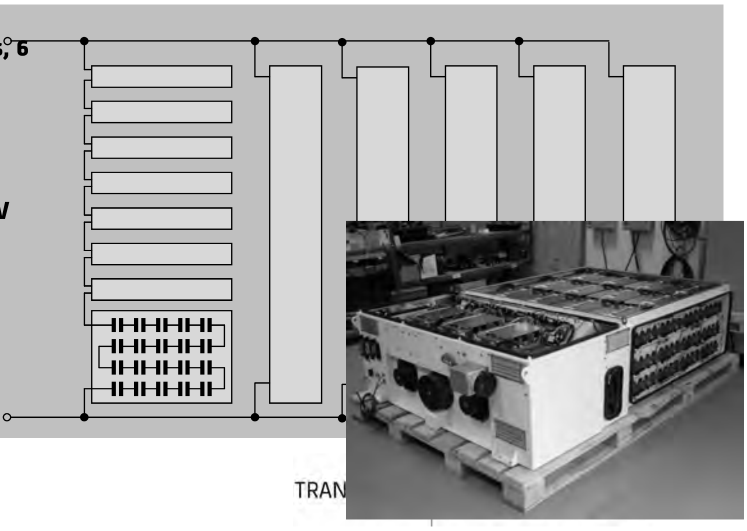
- **U = 2,5 V**
- **a single 2600F cell**



- **U = 50 V**
- **1 module = 20 cells connected in serial mode**

- **STEEM supercaps box : branches in parallel, modules in serie**

48 modules, 6 each of 8



- **U = 400 V**

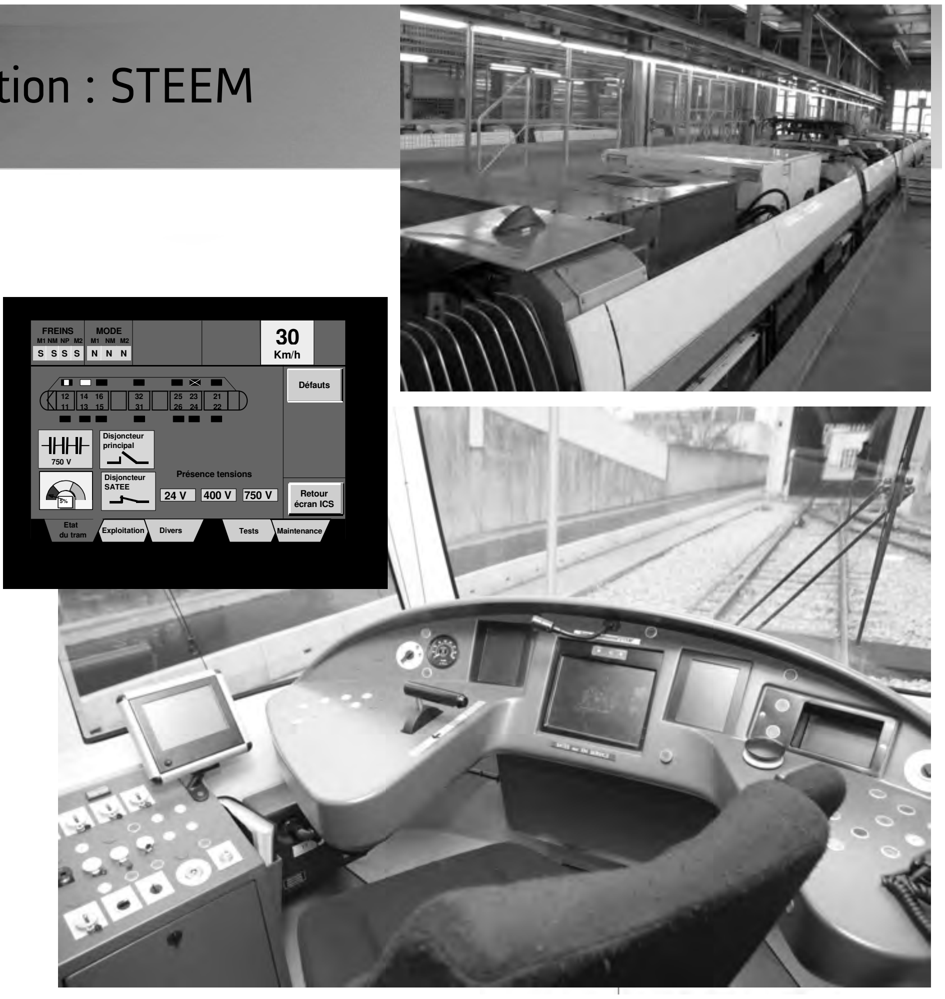
E = 1,62 KWh
$P_{soc\ 0}$ = 350 KW
$P_{soc\ 1}$ = 500 KW

Msc=720 kg

Recharge time 20 s min

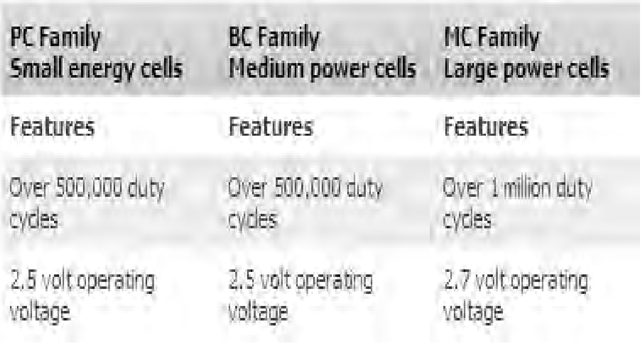
On-board Solution : STEEM

- Integration in roof layout
- Adapted HMI interface for driver including supercap gauge
- Risk of empty tank on autonomous sections



Supercapacitors constraints

Extract of MAXWELL supercapacitors data sheet :



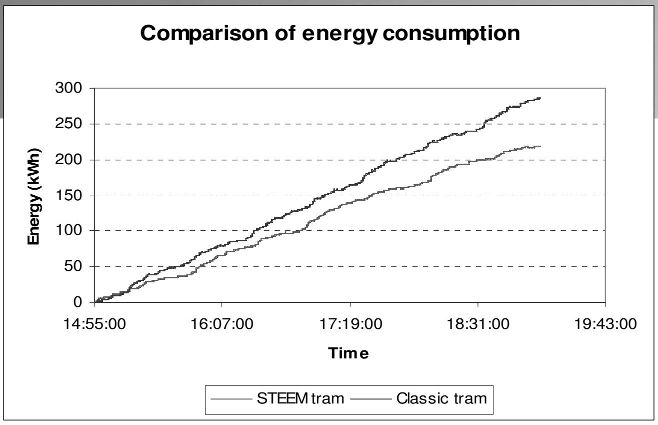
PC Family Small energy cells	BC Family Medium power cells	MC Family Large power cells
Features	Features	Features
Over 500,000 duty cycles	Over 500,000 duty cycles	Over 1 million duty cycles
2.5 volt operating voltage	2.5 volt operating voltage	2.7 volt operating voltage

- Average cycles per year : between 150 000 and 200 000, therefore :

Lifespan : between 5 and 7 years for a 25℃ operation ambient temperature

- **BUT lifespan is halved for each 10℃ above the nominal temperature of 25℃ and each 100 mV above nominal voltage (source : Supercapacitor traction system concept evaluation by Ing Frederik van Mulder)**
- **=> Supercapacitors refrigeration is compulsory !**

On-board Solution : STEEM



Energy saving effect depending on :

- number of trams-on-line
- heating and cooling (HVAC)
- Measured in spring 2010 : 13% average
- minimum 10%, maximum 18%
- highest savings : off-peak hours

Agenda

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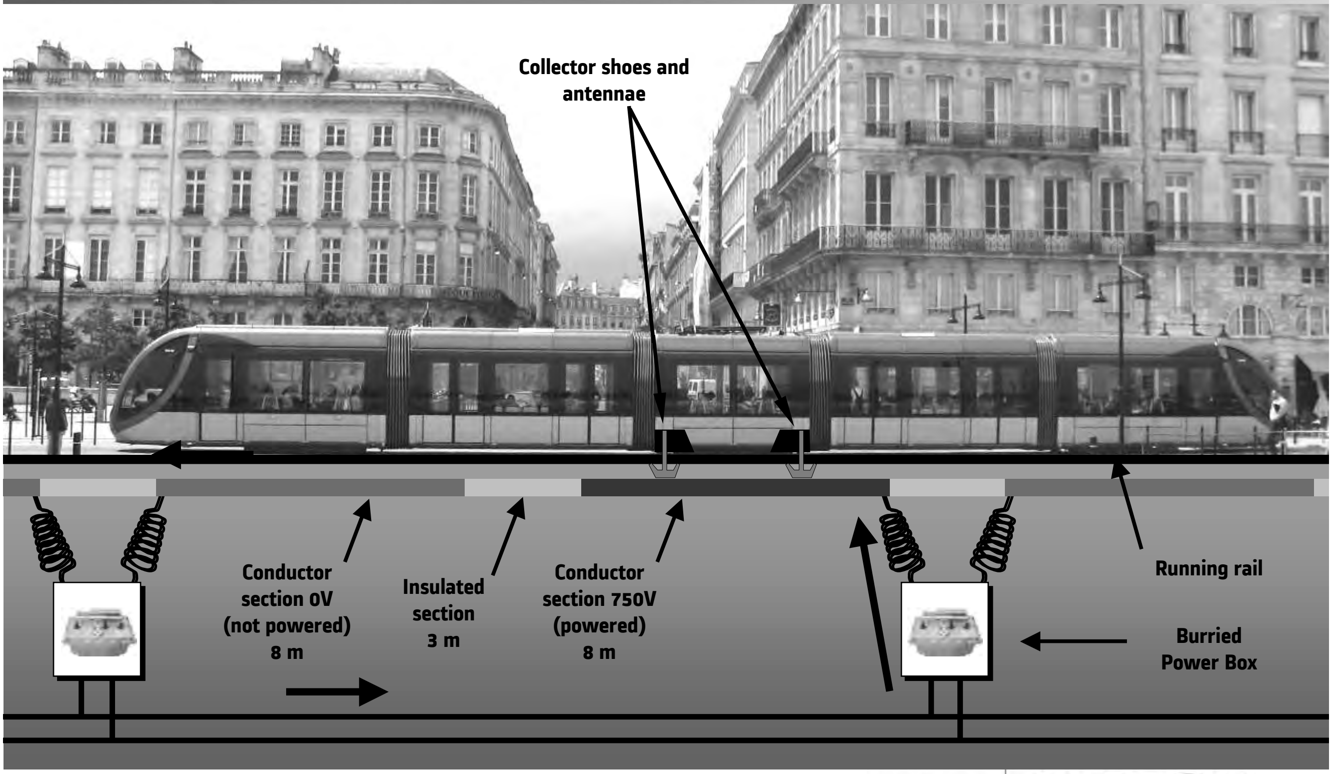
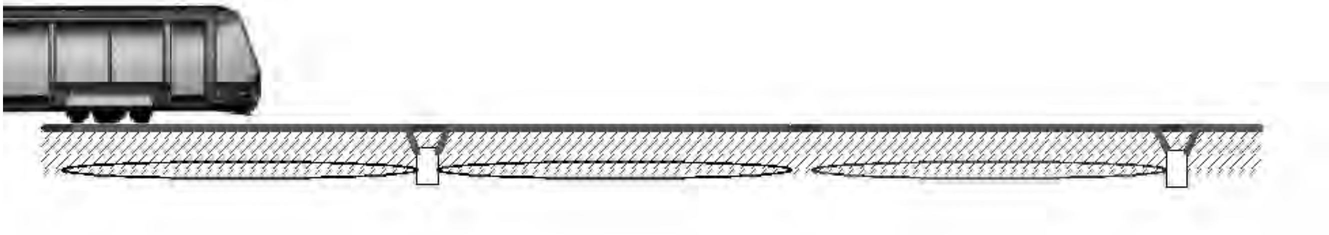
APS system: principles

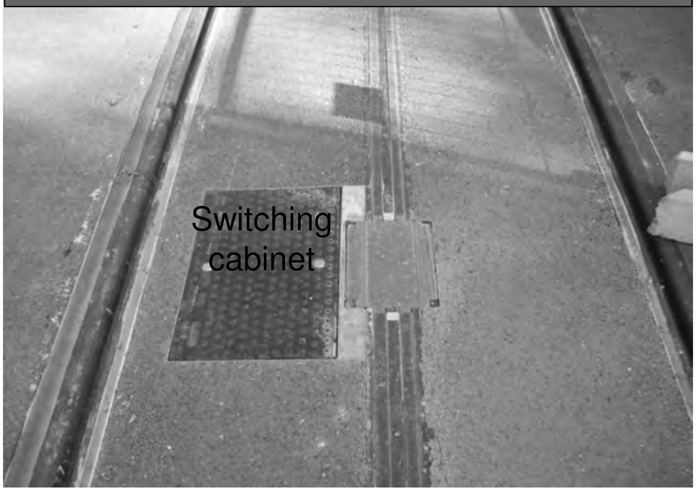

Collector shoes and antennae
Conductor section 0V (not powered) 8 m
Insulated section 3 m
Conductor section 750V (powered) 8 m
Running rail
Burried Power Box

APS system: principles



APS: Aesthetic Power Supply

- Segmented street-level power rail
- Conductive segments Switched off-on-off as tram progresses
- Safety rule: Conductive segments energized under tram only.



- Safety rule consequence: All segments outside tram at 0 Vcc

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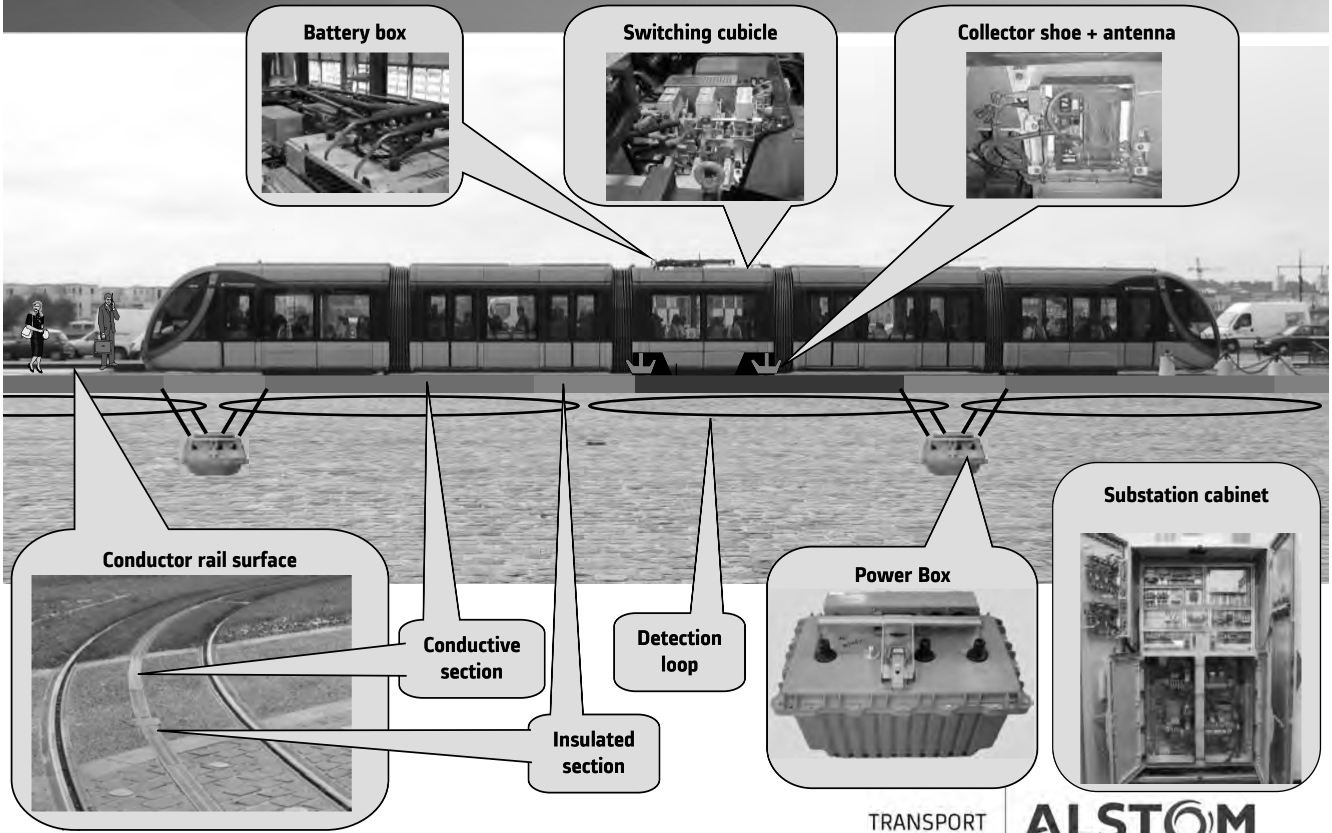
APS system: main components



Battery box

Switching cubicle

Collector shoe + antenna

Substation cabinet

Conductor rail surface

Conductive section

Detection loop

Power Box

Insulated section

Agenda

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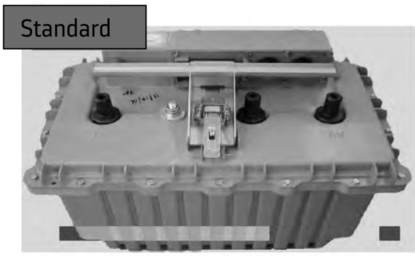
APS adaptation for hot climate

- **Objectives**
  - Tropical environment (hot, humid, sandy)

- **Technologies**
  - Thermic design of power box



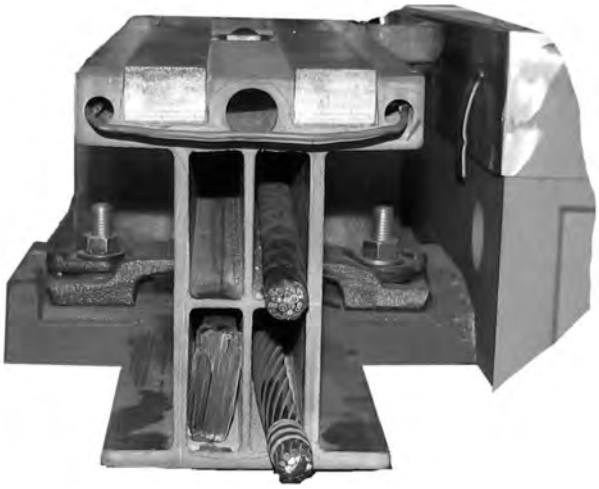
  - Deep cable ways
  - Air con substations
  - Hot humid air: cooled roof equipment
  - Sand and dust: brushes under tram, onboard cabinets sealed with internal heat exchangers or lightly over pressured
- **References** : Dubai & Brasilia

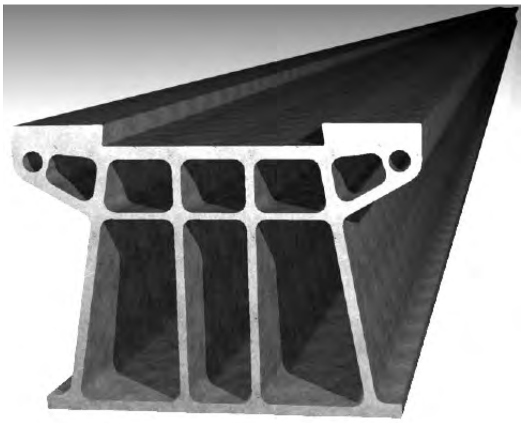
APS rail evolution

APS Bordeaux

Other APS projects

- wider rail for surface insulation
- wider loop for better train detection
- power cables centered (harmonics)
- stronger and better for installation





Running Rails

Keeping the Rail Free of Sand : A Proven Solution

- Purpose
  - Remove the sand from the grooved rail
- Solution
  - The Rail Vacuum Cleaner Vehicle

APS Rail

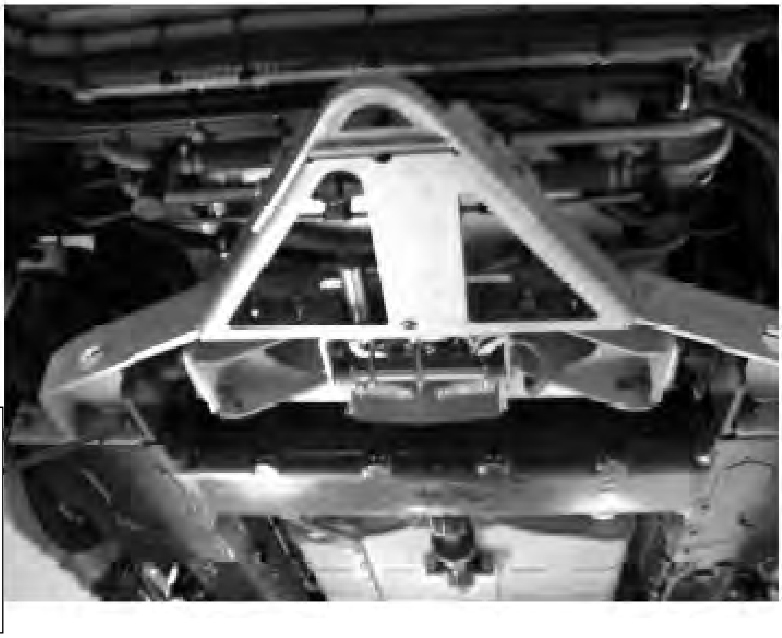
- Purpose
  - Remove all objects and pollutants from the APS rail surface
- Composition
    - A heavy duty shield to remove objects greater than 60 mm
    - A brush to remove lighter pollutants, **particularly dust and sand**

  Design to handle acceleration levels of 30 g's in all directions

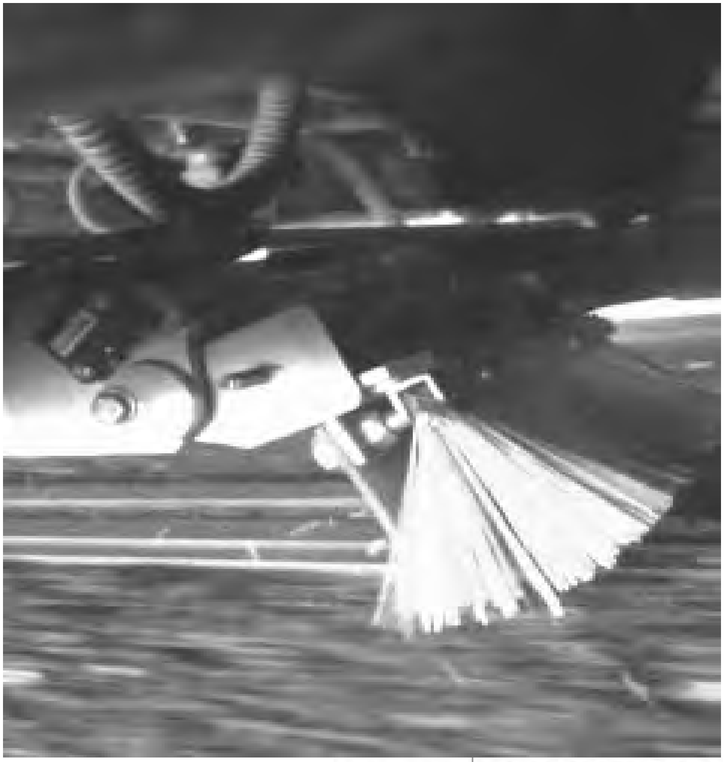
- Mounting
  - The device is mounted at each end of the tram
  - Activation is linked to the direction of travel

Keeping the APS Rail Clean/ A Robust Solution

INSTALLATION ON THE VEHICLE



Dust and Sand protection



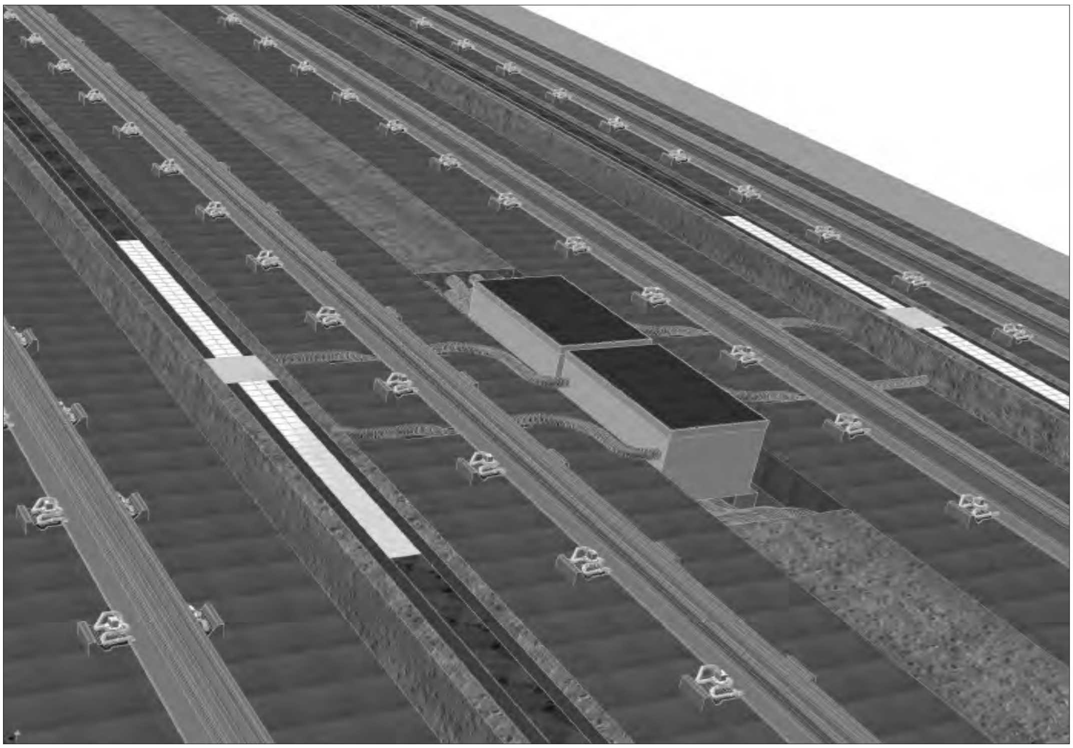
IN OPERATION in
BORDEAUX

Dust and Sand protection

Keeping the APS Rail Clean

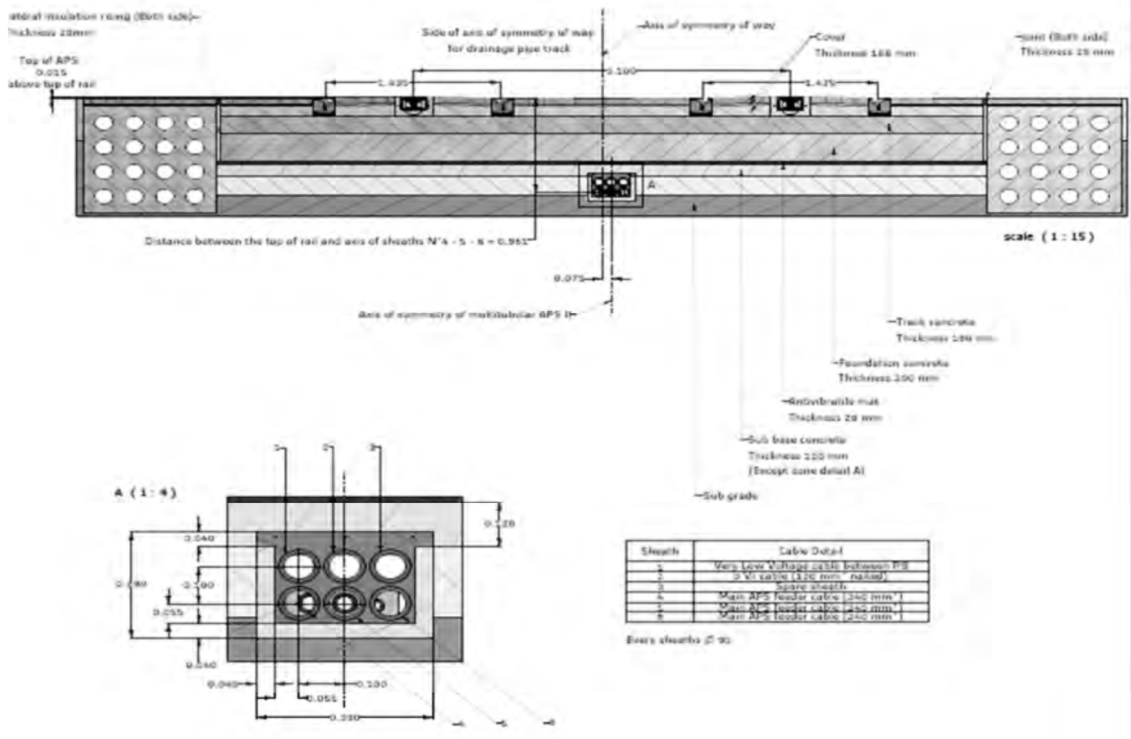
- Test Program completed
  - Shock Tests @ 20 kph with :
    - 1 kg metal chunk
    - 0.6 kg piece of wood
    - 4 kg concrete block
    - Stones & brick
    - Max acceleration recorded less than 20 g in all direction
  - Brush Test @ 15 & 18 kph with
    - Sand and gravel
    - Paper,
    - Plastic Bags
    - Wrappers

Power boxes arrangement



TYPICAL TRACK CROSS SECTION

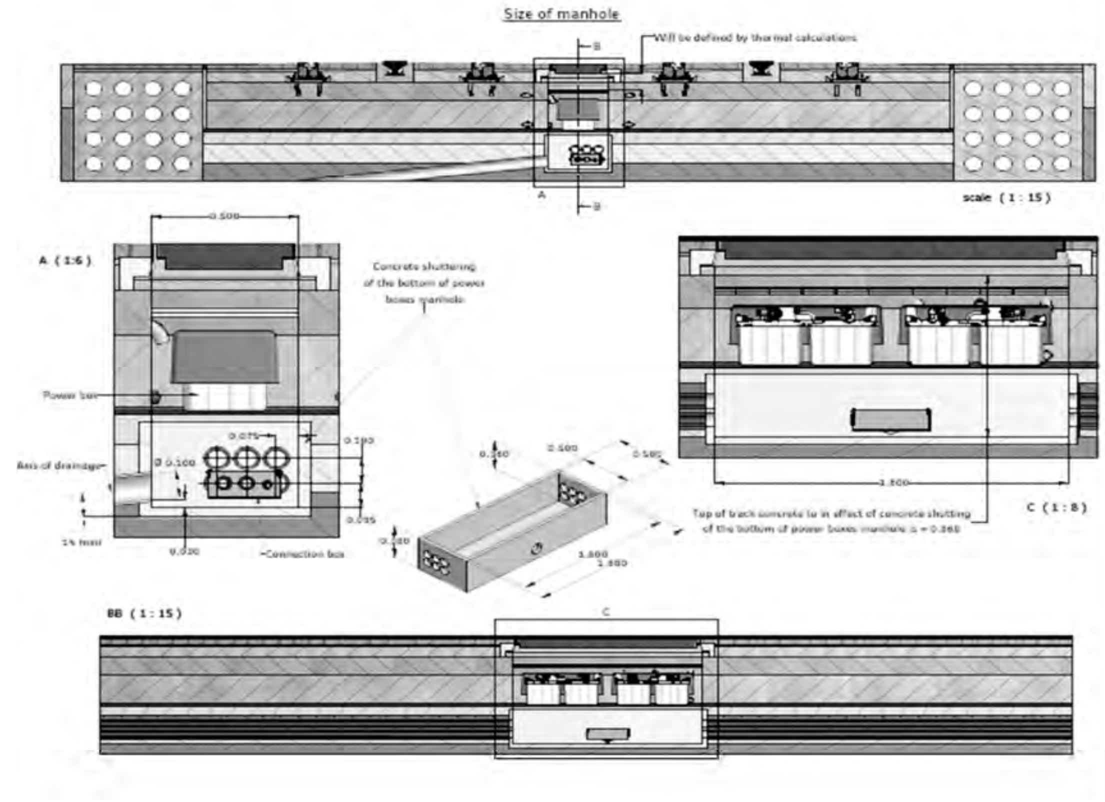
Typical track cross-section for floating slab in box for Junction



Sheath	Cable Detail
1	Very Low Voltage cable between PB
2	3 Vi cable (120 mm^2 naked)
3	Spare sheath
4	Main APS feeder cable (240 mm^2)
5	Main APS feeder cable (240 mm^2)
6	Main APS feeder cable (240 mm^2)

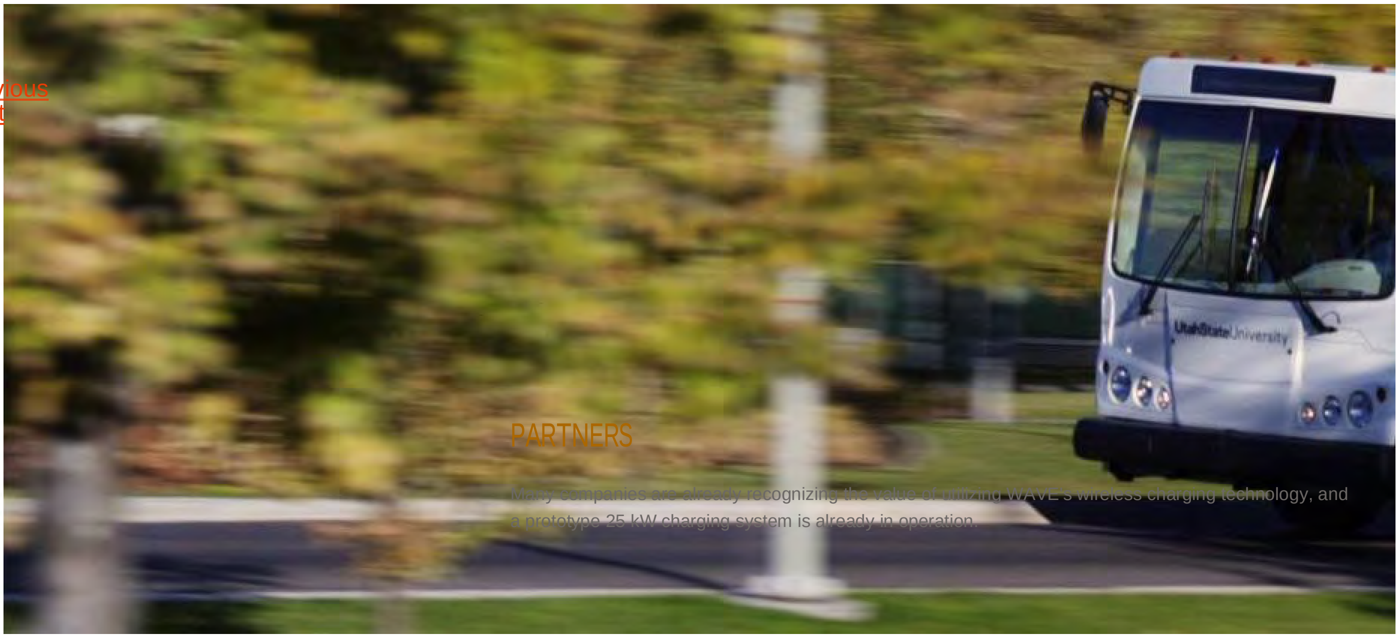
Every sheaths Ø 90

TYPICAL APS TRACK CROSS SECTION


Size of manhole
Will be defined by thermal calculations
B
A
B
scale (1 : 15)
A (1:6)
0.500
Concrete shuttering of the bottom of power boxes manhole
Power box
Axis of drainage
Ø 0.100
0.075
0.100
0.035
1% min
0.020
Connection box
0.150
0.500
0.500
0.180
1.800
1.800
1.800
Top of track concrete to in effect of concrete shutting of the bottom of power boxes manhole is = 0.365
C (1 : 8)
BB (1 : 15)
C

E-mail: info@waveipt.com

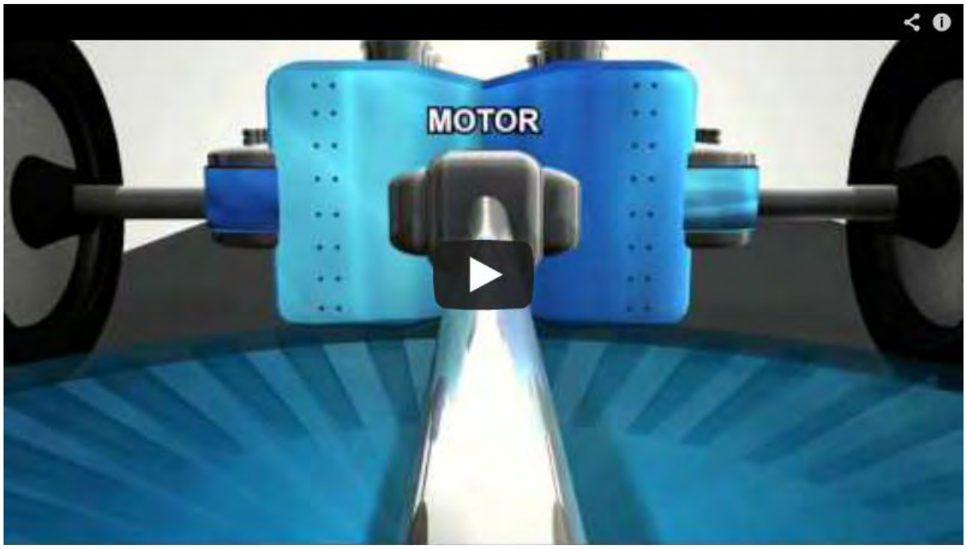
1
2
3
Previous
Next



PARTNERS

Many companies are already recognizing the value of utilizing WAVE's wireless charging technology, and a prototype 25 kW charging system is already in operation.

Watch Our Video



What Others Are Saying

> *What attracted us to this technology is the ability for us to power on the go and to have smaller batteries that allow us to get in and out of traffic throughout the day without a constant need for repowering.*

Carl Sedoryk, General Manager,
Monterey-Salinas Transit

> *With WAVE's wireless power transfer technology we're able to use fewer batteries, and get a lighter vehicle, which means that [wireless power transfer] can be economically viable and competitive with diesel.*

Alma Allred, University of Utah
Commuter Services

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Utah 2012 State of the State Address Mentions WAVE

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Induction Charging Comes to Public Transit

21 December, 2012 *Technology*

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Swaner EcoCenter
1258 Center Drive
PO Box 680941
Park City, UT 84068

801-633-1676

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Wireless Advanced Vehicle Electrification

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Induction Charging Comes to Public Transit

by Keith Barry
Wired
12.03.12

Say goodbye to catenary wires. Utah State University has unveiled an electric bus that charges through induction, topping off its batteries whenever it stops to pick up passengers.

Designed by USU's Wireless Power Transfer team and the Utah Science Technology and Research initiative's Advanced Transportation Institute, the prototype Aggie Bus is already on the road. It uses the same wireless charging principle as an electric toothbrush or a wireless smartphone charger, except optimized for a massive public-transit vehicle.

As in all modern inductive-charging setups, a transformer is "split" between the bus and a charge plate under the bus stop. When the bus drives over the charging plate, current flows with no physical contact required. Engineers at USU designed their system so that the Aggie Bus can be misaligned up to 6 inches from the charge plate and still get 25kW of power and 90 percent efficiency from the power grid to the battery.

Because of the fixed routes they run and frequent stops they make, induction charging is ideal for buses. Instead of charging up a massive battery overnight before a route, the Aggie Bus features a smaller battery setup that recharges every time the bus reaches a predetermined stop. The smaller batteries free up interior space, reduce downtime and lower battery costs — although induction plates must be added to bus stops.

Though the Aggie Bus is a working prototype, USU is working with Wireless Advanced Vehicle Electrification (WAVE) — a company spun-out from USU — in order to bring a commercialized bus to market. In mid-2013, WAVE and the Utah Transit Authority are planning to unveil a 40-foot induction-charged transit bus on the USU campus that's capable of taking a 50kW charge. The project was funded by USU, who will purchase the bus, and a $2.7 million grant from the Federal Transit Administration.

Charging a bus through induction may be a new idea in the U.S., but bus routes with similar wireless charging systems have been in place in Torino, Italy, since 2003 and Utrecht, the Netherlands, since 2010. Ideally, induction charging would be used in city centers to replace noisy, smoky diesel buses. It would also work on already electrified routes, allowing cities to take down unsightly hanging catenary wires.

wired.com

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PRIMOVE: Game-changing turnkey solution for tram systems

primove light rail

Liberating trams from overhead lines

In many ways, light rail vehicles are the ultimate form of eMobility. Yet despite being clean, silent and convenient, they have always been hampered by one disadvantage – catenaries. Catenary power systems are complex to install, demanding to maintain and and clutter the urban space with unattractive infrastructure.

Thanks to PRIMOVE contactless charging, trams can now run without any need for unsightly poles and overhead cables. The energy source is moved underground and charges the vehicle via inductive power transfer. It now becomes possible to integrate light rail systems into urban areas where conventional catenary networks are prohibited or unwelcome – such as city centres, parks, gardens and protected heritage sites. The cityscape is left untouched, minimising visual pollution and improving the overall appeal of the city.

Key benefits
System overview
Component features

Key benefits

Minimised visual pollution

- Elimination of wires and poles – all components are hidden under the vehicle and beneath the track
- Installation is possible even in previously unsuitable areas such as heritage-protected sites

Operational under all conditions

- Reliable even under adverse weather and ground conditions such as sand, snow or ice
- Compatible with all road surfaces or tracks

Reduced infrastructure

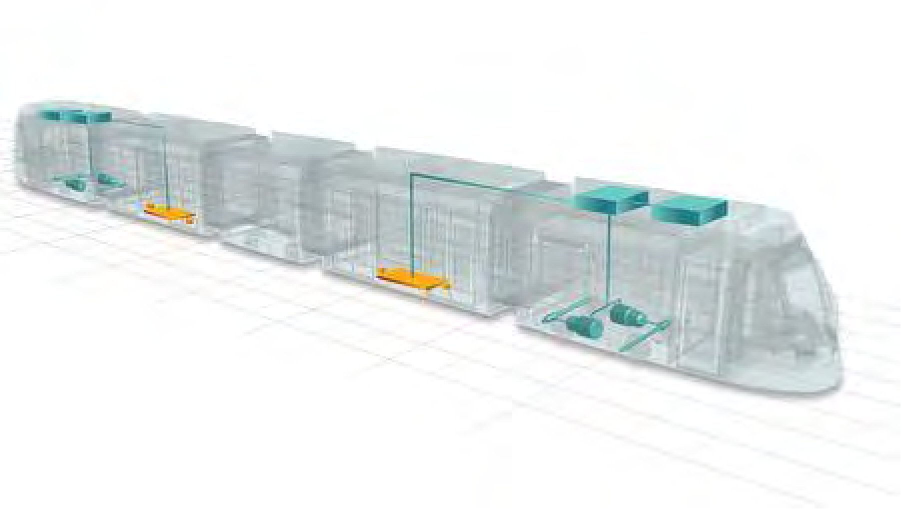
- Less land take needed than for catenary systems
- Less maintenance: no wear of pantographs and overhead lines, no risk of vandalism

No compromise on performance

- Same great performance as with catenary systems
- Reduction of energy consumption by up to 30% when combined with an energy storage solution

System overview

Because PRIMOVE is a contactless energy transfer solution, the system operates reliably under all circumstances – even in adverse ground conditions involving sand, snow or ice. Its liberation from the constraints of overhead cables also gives urban planners and public transport operators more freedom and flexibility in designing their transport solutions.

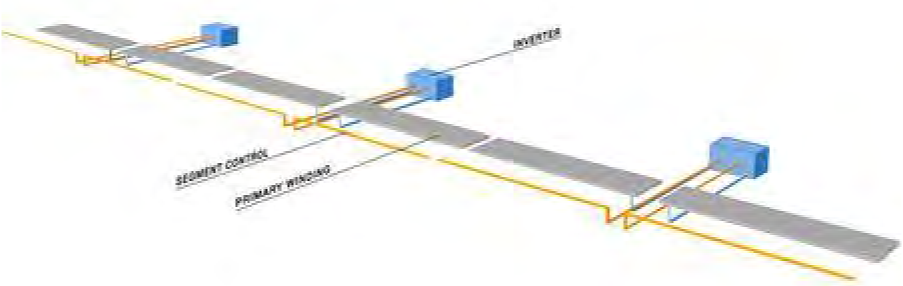


Beyond dispensing with overhead infrastructure, the PRIMOVE system also offers a whole range of further advantages. The technology is simple to install in both new and existing lines as the components easily fit between the rails. Initial investment and maintenance costs are lowered, making the overall system highly competitive and efficient. The charging system could even be made compatible with road vehicles, enabling the same underground infrastructure to be used for recharging multiple modes of public transport.

For even higher levels of efficiency and performance, PRIMOVE technology can be combined with an energy storage solution. When mounted on a light rail vehicle, this device stores the energy released when braking for later use. The system reduces energy consumption by up to 30%, lowering both electricity costs and greenhouse gas emissions. Over short distances,PRIMOVE-equipped trams can also operate without having to recharge, further minimising infrastructure and installation costs.

Component features

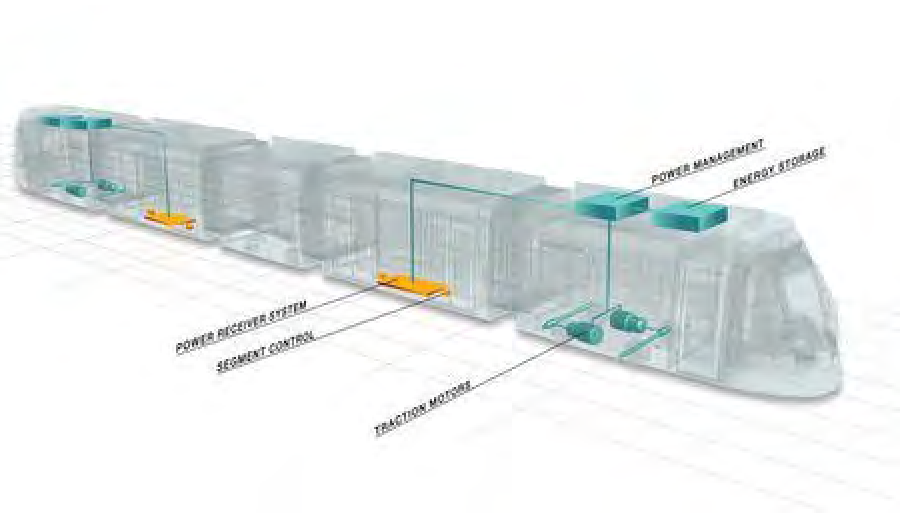
PRIMOVE wireless charging technology comprises two sets of components – wayside components that are buried underground and onboard components that are fitted onto the vehicle frame. Both sets are designed to enable maximum structural integration, as well as for energy transfer at high power and efficiency.



Wayside components

- Fully buried underground and can be covered with different materials like asphalt or concrete
- Primary cable segments provide the actual power transfer to the vehicle and are installed just under the road surface
- Magnetic shielding under the primary winding (magnetic layer) prevents electromagnetic interference
- The Vehicle Detection and PRIMOVE Segment Control (VDSC) cable senses when a PRIMOVE-equipped vehicle is above the segment and switches the segment on. Segments otherwise remain inactive to comply with electromagnetic interference protection requirements
- The Supervisory Control and Data Acquisition (SCADA) interface provides information for system control and diagnostics

- Inverters convert the DC supply voltage to the AC voltage used in the system.
- DC feed cables supply power to the inverters



Onboard components

- The PRIMOVE Power Receiver System consists of the pick-up together with a compensation condenser, which are both installed underneath the vehicle. They convert the magnetic field from the primary winding into alternating current
- Inverters convert the alternating current from the pick-up into direct current that powers and charges the vehicle
- Energy storage solution
- The Vehicle Detection and PRIMOVE Segment Control (VDSC) antenna detects cable segments and coordinates the on/off switching

primove

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- Inductive power transfer
- High power transfer
- Opportunity charging

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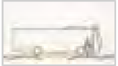


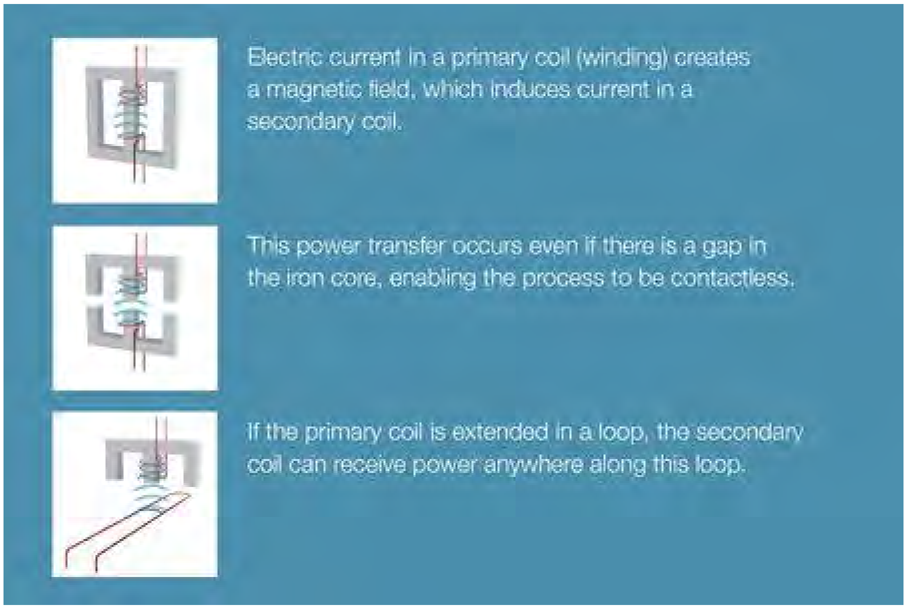
PRIMOVE: High power transfer for electric buses

The technology behind primove

Based on the principle of inductive power transfer, PRIMOVE technology allows energy to be wirelessly transmitted between components buried underground and receiving equipment installed beneath the vehicle.

The inductive principle functions as follows: an electric conductor creates a magnetic field, which generates an electric current in another conductor placed within that field. When applied in conjunction with the PRIMOVE system, this electric current generates energy that is then used to propel vehicles forward in a clean, efficient way.

In order to power vehicles through inductive power transfer, an induction coil under the road or track carries high-frequency alternating current (AC), thereby creating a magnetic field. This field induces a voltage in the vehicle-side inductive power receiver (pick-up), which is used to charge and power the vehicle. Wayside components “communicate” with the vehicle to ensure that charging segments are only switched on when the vehicle is positioned directly above them.



Electric current in a primary coil (winding) creates a magnetic field, which induces current in a secondary coil.

This power transfer occurs even if there is a gap in the iron core, enabling the process to be contactless.

If the primary coil is extended in a loop, the secondary coil can receive power anywhere along this loop.

This principle is used in a huge range of applications from electric toothbrushes that charge inductively when placed on their base to electric generators in power plants.

The charging process

When charging statically, the electric vehicle simply drives to a charging point; once the vehicle is positioned over the charging segment, energy transfer can begin. The PRIMOVE system allows for energy transfer at high levels, minimising both charging time and frequency. The driver does not have to follow any special procedure, nor does he require extra qualifications or training to operate the system. Furthermore, there is never any physical contact with electricity, ensuring that the charging process is both safe and driver-friendly.

When charging dynamically (in motion), the rail or road vehicle recharges by driving over the inductive segments. These are automatically switched on as the vehicle is activated by the wayside detection system.

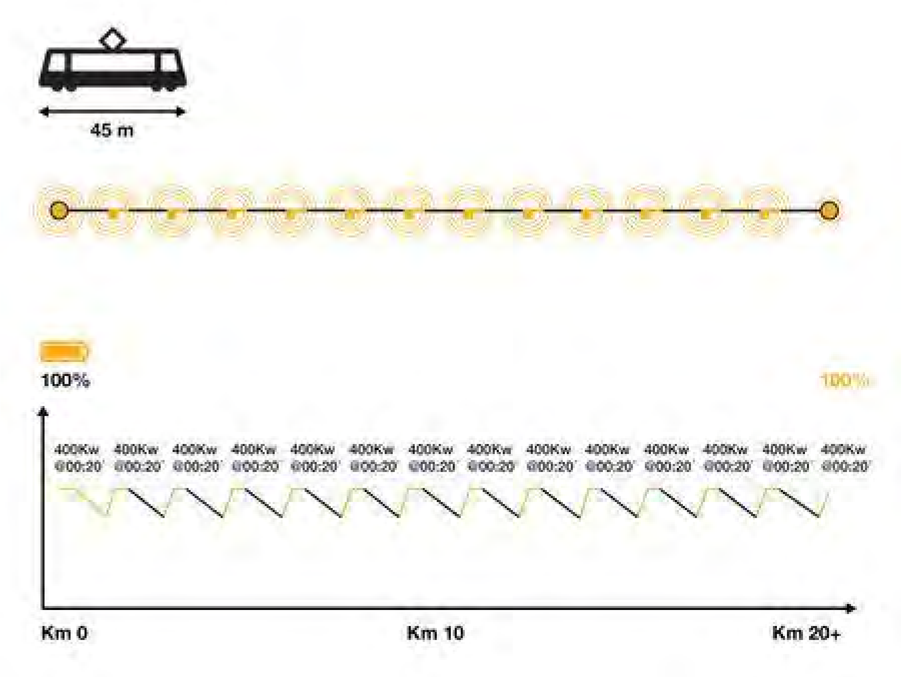
Introducing high power opportunity charging

Range and recharging constraints are the key concerns when it comes to converting an entire delivery fleet or bus network to electric power. In order to address these issues while offering a solution that is light, easy to integrate and competitive, the PRIMOVE system combines a charging pattern at regular intervals with energy transfer at high power levels. The charging process is seamlessly integrated into existing operations, thereby ensuring uninterrupted service without any need for additional fleet vehicles or batteries.

A precise energy flow simulation helps define the optimal infrastructure to maximize efficiency while keeping charging frequency (and infrastructure) to a minimum. It defines the ideal positioning of charging points that match the existing route so that the vehicle never has to change its course or extend dwell time to recharge.

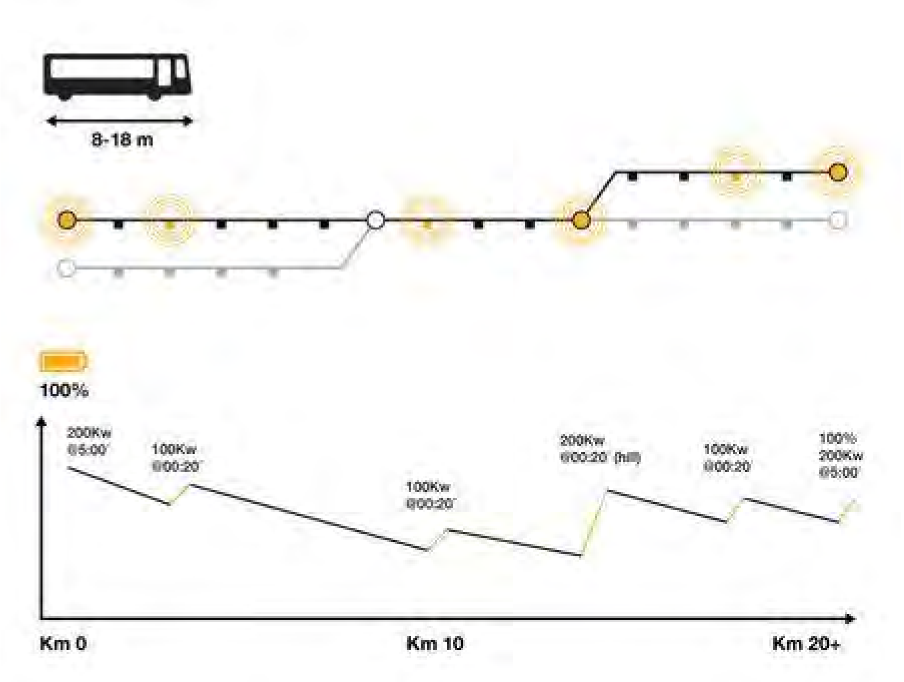
Light rail

Charging segments are integrated at every tram stop and the subsequent few metres to enable recharging while letting passengers on/off and during acceleration.



Bus

Charging stations are positioned in the depot and/or en route at bus stops for recharging while letting passengers on/off without extended dwell times.



Automotive

Charging stations are installed at strategic points (e.g. loading docks for delivery vans, taxi ranks in airport waiting areas, supermarket parking spaces) to allow fast charging at convenient times when the vehicle is periodically not in use.

IRJ
international railway journal

Wednesday, August 15, 2012

Induction in action

Written by Keith Barrow

4

Emerging technologies are helping light rail operators to escape some of the visual, operational and financial restrictions of overhead catenary. Keith Barrow reports from Augsburg on the development of Bombardier's induction-based Primove system.

ONE of the defining trends in light rail technology over the last few years has been the emergence of catenary-free systems. Advances in supercapacitor and battery technology have spawned an array of catenary-free solutions and almost all of the major LRV manufacturers have developed their own products, many of which are now being offered commercially.

Bombardier's Primove system draws electrical energy through induction, using the same principles of power transfer used in an electric toothbrush. Primove LRVs draw power from a cable buried beneath the running rails which forms part of a primary circuit. This produces a magnetic field, which is converted back to electrical energy by a pick-up coil mounted underneath the vehicle. A short section of the cable, or primary winding, is only energised as the vehicle passes overhead, and can be safely laid under any surface, including tarmac, concrete, and grass.

A typical low-floor LRV would be equipped with two underfloor power receivers, each feeding roof-mounted power management and energy storage units at either end of the vehicle, which are also fed by the regenerative braking system. The power management unit feeds energy back to the traction motors as required.

Primove can operate with a supply voltage of 400-600V ac or 750V dc. The supply is fed to wayside inverters to power the vehicle detection antenna loop, which is laid alongside the track, and the primary winding, which is laid in 9m-long sections between the running rails. The primary winding is energised only when the vehicle passes overhead. Like the primary winding, the inverters and power supply network can be covered with any surface. Depending on the characteristics of the route, 10-25% of a typical light rail line would be equipped with the wayside equipment.

The system has charging power of 200kW, which feeds two 48kWh batteries with a transfer efficiency of up to 95%. Each battery weighs around a tonne - roughly the equivalent of 13 standing passengers - can load fully in 20 seconds, and has a 10-year service life expectancy under normal operating conditions.

The technology allows vehicles to charge dynamically or statically, which means Primove-equipped vehicles continue to draw current while standing at stations but use less power than conventional trams when in motion. This inevitably has an impact on the power supply architecture, and Bombardier says a line operating exclusively with Primove requires fewer substations than a line with standard catenary.

"The key to Primove is energy management," says Bombardier's Primove product director Mr Harry Seiffert. "It's all about achieving a trade-off between stress on the battery and the power supply infrastructure. The fact that there is no return current to the rail is also a key advantage."

Bombardier engineers first conceived Primove in 2003, and following a period of further development including input from the University of Braunschweig, it set up a 1km test track at its Bautzen plant in eastern Germany in 2009. Here a 30m-long Flexity LRV was tested at up to 40km/h on a 6% gradient.

The next step was to test the operating performance and electromagnetic compatibility of the system in an urban environment. In June 2010 Bombardier began installation of Primove on the 800m-long branch of Augsburg Line 3 to the city's exhibition centre, a project implemented in cooperation with the Augsburg Transport Authority (SAV) with grant funding from the German Federal Ministry of Transport Building and Urban Development (BMVBS). Test operation began in September 2010, using a bidirectional Flexity low-floor LRV, and the system was approved for limited passenger use a year later.

During this evaluation phase, Bombardier engineers worked with external assessors such as Tüv Süd to ensure Primove achieved all applicable electromagnetic compatibility standards, including the guidelines of the International Commission on Non-Ionising Radiation Protection.

Bombardier says a new LRV equipped with Primove costs around 10% more than a standard vehicle, although it aims to achieve equivalent operating performance and cost to catenary-based systems on a life-cycle basis, and even exceed the capabilities of overhead electrification in areas such as energy consumption. "It's clear trams won't run on Primove unless we are competitive on cost, so we need to be in the same range as conventional vehicles because cost is important to the market," explains Bombardier Transportation CEO Mr André Navarri. "You also have to factor in the price of the overall system, and the charging strategy for the line. The price of Primove components will decrease over time, and our simulations have demonstrated the system is cost-effective on a whole-life basis."

In addition to the elimination of unsightly catenary masts, Primove can also reduce the land area required for light rail projects. A double-track line with Primove requires a 7.05m-wide corridor, compared with the 7.6m footprint of a line equipped with overhead catenary.

Bombardier is pitching Primove as a system that completely obviates the need for catenary, while maintaining or improving on the performance of overhead electrification. The system is totally weather independent, and the Primove demonstrator has been successfully put through its paces in heavy snow and over sand-covered track with no loss of performance.

But what really sets Primove apart from competing catenary-free technologies is the potential of the system beyond light rail. A 125m-long setion of public road in the Belgian town of Lommel has been equipped with Primove, and tests are underway with a bus and a car. In June Bombardier and Braunschweig Transport launched a BMVBS-supported project to test two Primove-equipped buses on a 12km bus route in the German city. Bombardier is also extending the technology to commercial vehicles and is testing a van with a new prototype power receiver for smaller road vehicles at its eMobility facility in Mannheim.

Bombardier anticipates that the global electric bus market will represent 235,000 new vehicles over the next decade, and the value of the electric bus/taxi market is expected to increase from $US 6.24bn to $US 54.1bn by 2021. As light rail systems are almost universally electrified, the arguments in favour of adopting induction technology are naturally quite different from those for road vehicles. But the extension of Primove to other modes means economies of scale and the commonality of components could help to make this innovative technology even more accessible for future light rail projects.

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EcoActive Technologies

PRIMOVE

Catenary-Free Operation

In many city centres overhead lines and their surrounding infrastructure contribute to visual pollution of historic streets, parks or architectural landmarks. Catenary-free tracks for trams and light rail vehicles heighten the attractiveness of a city and provide for unobstructed views.

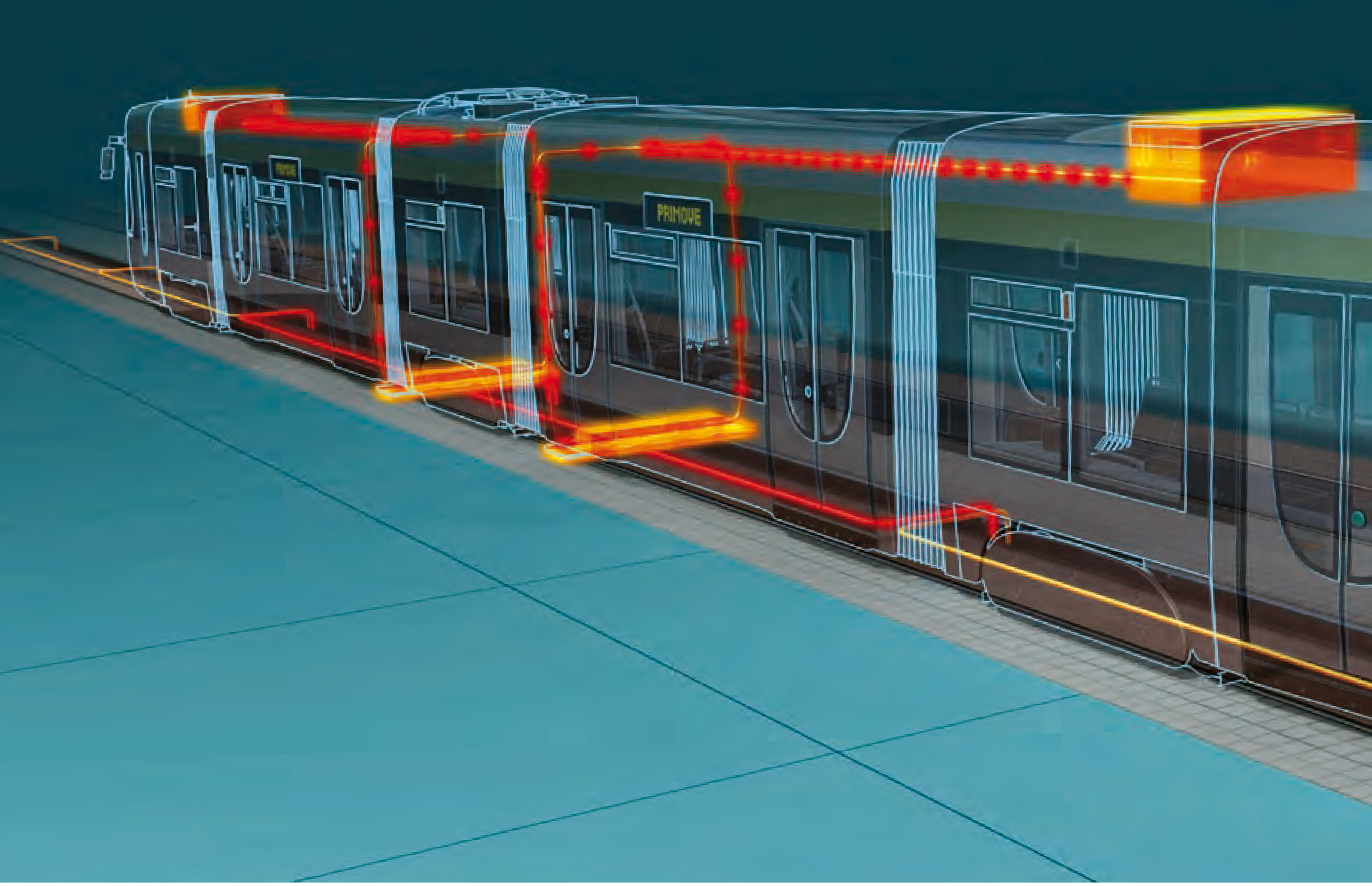
A world-premiere: contactless power transfer for urban rail vehicles

The new and unique *BOMBARDIER* PRIMOVE** system allows catenary-free operation of *FLEXITY** trams over distances of varying lengths and in all surroundings as well as on underground lines – just like any conventional system with overhead lines. What makes it outstanding is that the power transfer is contactless; the electric supply components are invisible and hidden under the vehicle and beneath the track.

The benefits are evident:

- Elimination of overhead wires – increasing a city's attractiveness
- Safe inductive power transfer
- No wear of parts and components
- Resistant to all weather and ground conditions including storms, snow, ice, sand, rain and water

The *PRIMOVE* system is connected to the *BOMBARDIER* MITRAC** Energy Saver, which stores electrical energy that is gained during operation and braking on board the vehicle by using high-performance double layer capacitor technology. Doing so optimizes power supply and saves energy.



Catenary-free operation – energy flow

Bombardier is at the forefront of continuously improving rail transportation as an ecologically leading mode of transport

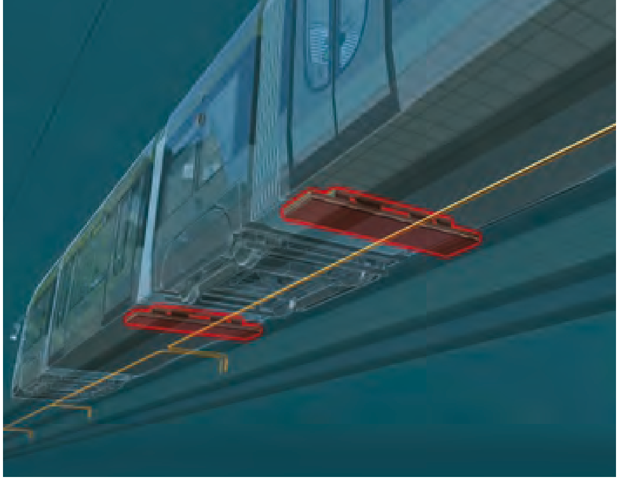
Preserving our environment by reducing emissions and using energy resources in an efficient and responsible way are undoubtedly major challenges which communities all over the world face today. Exhaust emissions and noise are some of the main factors that lead to a deterioration in the quality of life in our cities. In urban transport, railbound operations are making a major contribution to relieving congestion as well as cutting CO_2 and noise emissions.

Why Catenary-Free operation?

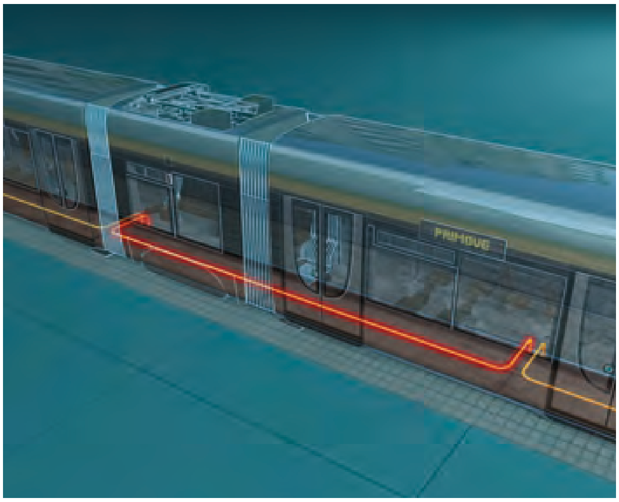
In addition to these well-known factors, municipal authorities are increasingly facing visual pollution caused by power poles and overhead lines obstructing the visibility of landmark buildings and squares. With *PRIMOVE* catenary-free operation trams can even run through heritage-protected areas, such as parks and gardens, historic market and cathedral squares, where conventional catenary systems are not permitted, thus preserving natural and historic environments. Additionally, when planning a new system or extensions catenary-free operation will contribute to an attractive and forward-looking appearance.

PRIMOVE Catenary-free operation – safe, cost-efficient, reliable and flexible:

- Due to invisible and contactless power supply, operation of the *PRIMOVE* catenary-free system is safe for pedestrians and other road users such as bikes, motorbikes or cars
- With no direct contact during energy transfer there is no wear of parts and components which keeps service and maintenance costs at a minimum – the initial construction costs lie far below those of any comparable solution on the market
- Reliable performance in all weather and ground conditions
- Same vehicle performance as with conventional catenary systems
- With the on-board *MITRAC* Energy Saver the system can continuously recharge the energy levels needed for uninterrupted maximum performance
- The *PRIMOVE* system can be tailored to the individual needs of each city: it is adaptable to different topographical conditions, performance expectations and distances



Pick-up coils



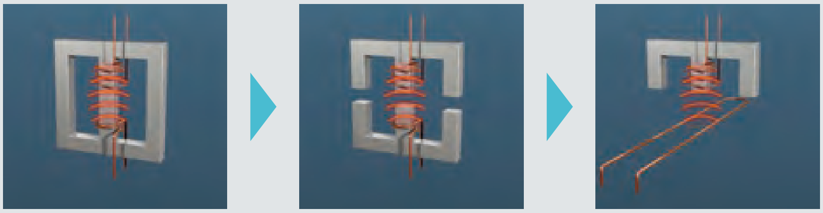
Underground cables

How does the PRIMOVE system work?

When running on conventional systems, trams and light rail vehicles take their energy from an overhead electrical line. Equipping the tracks and the vehicle with the *PRIMOVE* components also allows operation without a catenary. Cables laid beneath the ground are connected to the power conditioning and supply network. They are only energized when fully covered by the vehicle, which ensures safe operation. A pick-up coil underneath the vehicle turns the magnetic field created by the cables in the ground into an electric current that feeds the vehicle traction system.

Inductive power transfer principle

The functional principle is based on the inductive power transfer of a transformer (see illustration below) – a principle that is up to now has only been used in certain industrial applications (in the automotive industry for transportation systems in manufacturing) or with household appliances (i.e. electric toothbrush).



Transformer

Air gap in iron core

Primary winding
extended as loop

Bottom iron core removed

Working principle –
inductive power transfer

PRIMOVE Catenary-Free Operation

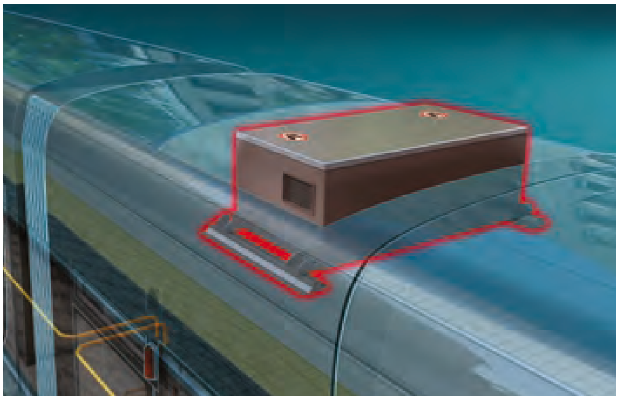
MITRAC Energy Saver

The vehicle mounted *MITRAC* Energy Saver stores the energy gained during braking and is constantly charged up during operation, either when the vehicle is in motion or waiting at a stop, picking up the power from the underground section. Doing so allows both maximum vehicle performance and constant inductive power levels, ensuring continuous operation of the vehicle just like conventional catenary systems.

Testing at Bombardier in Bautzen

The new *PRIMOVE* catenary-free solution is undergoing extensive testing at the test track of the Bombardier site in Bautzen, Germany. A low-floor tram and the test track are equipped with the *PRIMOVE* components and different phases simulating regular operation are being carried out.

ECO4 – Energy, Efficiency, Economy and Ecology
***PRIMOVE* catenary-free operation forms part of Bombardier's *ECO4** environmentally friendly technologies. Addressing the growing challenges among operators to reduce Energy consumption, improve Efficiency, protect the Ecology while making sense Economically, *ECO4* is the concrete validation of Bombardier's declaration – *The Climate is Right for Trains**.**



MITRAC Energy Saver

Performance of the PRIMOVE System

- 250 kW continuous output of the *PRIMOVE* system, designed for a typical light rail vehicle (30 metres long, operating at a speed of 40 km/h with a gradient of six percent). A prototype vehicle is currently undergoing tests at Bombardier in Bautzen
- Performance can be provided to vary from 100 to up to 500 kW, depending on the respective vehicles and system requirements: length and number of vehicles, topographic conditions, range of application

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Bombardier Transportation
Hermann Gebauer Strasse 5
1220 Vienna, Austria

Tel +43 1 25110 760
Fax +43 1 25110 335

www.bombardier.com

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primove
Wireless eMobility

Change the way to charge

BOMBARDIER
the evolution of mobility

No emissions
No wires
No hassle

eMobility redefined

The BOMBARDIER PRIMOVE solution is a game-changing technology that enables the wireless charging of electric vehicles. Based on inductive power transfer, the PRIMOVE system liberates eMobility from the constraints of cables, wires and plugs – making urban transport more flexible and convenient than ever before.

The innovative PRIMOVE system provides a contactless power source for all types of electric transport – from light rail and bus networks to commercial vehicles and cars.

Discover how the PRIMOVE solution is ready to transform the eMobility landscape today.

The primove advantages

Invisible

The principle of inductive power transfer allows energy to be transferred in a contactless manner – no more plugs, wires or overhead cables. The necessary components are buried underground and hidden beneath the vehicle, making the PRIMOVE solution a safer, less cluttered system that gives urban planners and public transport operators more freedom over the design of urban mobility solutions.

Clean and quiet

Electric vehicles generate no emissions at the point of use – no carbon dioxide, no noxious gases, no particulates. This brings significant and sustainable improvements in air quality, thereby raising the level of passenger comfort and making the urban environment cleaner and more pleasant for its residents.

No recharging constraints

Due to the high level of power that can be transferred with the PRIMOVE system, vehicles can recharge quickly enough to avoid lengthy waiting periods. Regular stops are turned into convenient charging opportunities that have no disruptive effect on the timetable. This means that vehicle availability and service reliability can be ensured.

Flexible and reliable

PRIMOVE technology offers a variety of charging solutions for all electric vehicles that is compatible with all weather and ground conditions. It can be adapted to any city, course and topography – perfect for fast-tracking the acceptance of sustainable mobility practices.

Convenient

Thanks to the intelligent vehicle detection function that makes the charging process fully automated, recharging is driver-friendly and hassle-free. No specific training or qualifications are required and the driver never comes into contact with electricity, ensuring that the entire process is safe.

Competitive

The PRIMOVE solution makes the electric vehicle market competitive and attractive again. By maximising the concept of opportunity charging at high power levels, the PRIMOVE system reduces total cost of ownership and provides an affordable and attractive solution without reverting to impractical solutions like battery swapping.

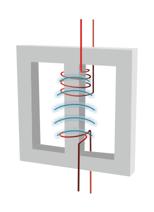
Easy integration

The PRIMOVE system is quick and easy to install. Prefabricated and tested modules can easily be integrated into any ground surface and the system can be fitted onto any new or existing rail or road infrastructure. It has no moving parts and only a small number of components, all of which are buried underground or hidden beneath the vehicle. This significantly minimises wear and tear, while guaranteeing protection against vandalism. The result is lower maintenance costs and higher service reliability.

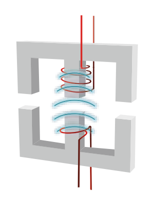
The technology behind primove

The inductive principle

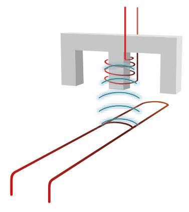
Based on the principle of inductive power transfer, PRIMOVE technology allows energy to be transmitted without contact between components buried underground and receiving equipment installed beneath the vehicle. The principle functions as follows: an electric conductor creates a magnetic field, which generates an electric current in another conductor placed within that field. When applied in conjunction with the PRIMOVE system, this electric current generates energy that is then used to propel vehicles forward in a clean, efficient way.



Electric current in a primary coil (winding) creates a magnetic field, which induces current in a secondary coil.



This power transfer occurs even if there is a gap in the iron core, enabling the process to be contactless.



If the primary coil is extended in a loop, the secondary coil can receive power anywhere along this loop.

Introducing high power opportunity charging

Range and recharging constraints are the key concerns when it comes to converting an entire delivery fleet or bus network to electric power. In order to address these issues while offering a solution that is light, easy to integrate and competitive, the PRIMOVE system combines a regular charging pattern with energy transfer at high power levels. The charging process is seamlessly integrated into existing operations, thereby ensuring uninterrupted service without any need for additional fleet vehicles or batteries.

Light rail

Charging segments are integrated at every tram stop and the following few metres to enable recharging while letting passengers on/off and during acceleration.

Bus

Charging stations are positioned in the depot and/or en route at bus stops for recharging while letting passengers on/off without extended dwell times.

Automotive

Charging stations are installed at strategic points (e.g. loading docks for delivery vans, taxi ranks in airport waiting areas, supermarket parking spaces) to allow fast charging at convenient times when the vehicle is periodically not in use.

primove light rail
Liberating trams from overhead lines

In many ways, trams and light rail vehicles are the ultimate form of eMobility. Yet despite being clean, silent and convenient, they have always been hampered by one disadvantage – catenaries. Catenary power systems are complex to install, demanding to maintain and clutter the urban space with unattractive infrastructure.

Thanks to PRIMOVE contactless charging, light rail vehicles can now run without any need for unsightly poles and overhead lines. The energy source is moved underground and charges the vehicle via inductive power transfer. It now becomes possible to integrate light rail vehicles into urban areas where conventional catenary networks are prohibited or unwelcome – city centres, parks, gardens and protected heritage sites. The cityscape is left untouched, minimising visual pollution and improving the overall appeal of the city.

No compromise on performance

- Same great performance as with catenary systems
- Reduction of energy consumption by up to 30 % when combined with an energy storage solution

Minimised visual pollution

- Elimination of wires and poles – all components are hidden under the vehicle and beneath the track
- Installation is possible even in previously unsuitable areas such as heritage-protected sites

Reduced infrastructure

- Less land take needed than for catenary systems
- Less maintenance: no wear of pantographs and overhead lines, no risk of vandalism

Operational under all conditions

- Reliable even under adverse weather and ground conditions such as snow, ice and sand
- Compatible with all road surfaces and tracks

Augsburg, Germany

Demonstrating safe high power inductive charging for trams

In September 2010, Bombardier Transportation installed the contactless and catenary-free PRIMOVE system for trams on a 600-metre section of Line 3 to the Augsburg trade fair centre. The pilot project is being co-funded by the German Federal Ministry for Transport, Building and Urban Development (BMVBS) and realised in cooperation with the Augsburg Transport Authority (Stadtwerke Augsburg Verkehrs-GmbH) with the aim of demonstrating reliable operation under the real conditions of daily operation in an urban environment.

Federal Ministry
of Transport, Building
and Urban Development

Facts & figures

Start of operations:
September 2010

Vehicle type:
1 Bombardier bidirectional low-floor tram

Charging power:
200 kW

Lommel, Belgium

Taking the primove concept to the road

In October 2010, Bombardier joined the Flanders' DRIVE project in Lommel (Belgium), in which a consortium of industrial companies and R&D specialists came together to research the potential of inductive charging for electric road vehicles.

The project demonstrates high power transfer in both dynamic and stationary use, as well as the intermodal charging compatibility of the system. The project also demonstrates the system's operational efficiency in a real urban environment, on different road surfaces and under all weather conditions.

Facts & figures

Start of operations:
October 2010

Vehicle type:
1 Van Hool bus, 1 Volvo C30 car

Charging power:
40 kW & 80 kW (bus), 22 kW (car)

primove bus
Going electric

The bus market is experimenting with alternatives to combustion-driven vehicles, but few of these approaches offer a sustainable solution to our dependence on fossil fuel. More often than not, they involve serious compromises in vehicle availability, service reliability, aesthetics, or resources (e. g. battery swapping, requiring extra fleet vehicles or turning to conductive charging). In essence, these solutions fail to address the key issue of making the electric bus market competitive and attractive.

PRIMOVE technology represents a major leap forward by offering a wireless charging system that is easy to install and convenient to use. By incorporating high power charging at the most convenient points along bus routes, the PRIMOVE system ensures optimum fleet availability. The wireless charging process is seamlessly integrated into existing operations to allow uninterrupted service without reverting to impractical, unattractive or unaffordable solutions.

Smaller, lighter system

- Extends battery life and lowers energy consumption
- Vehicles can carry passengers, rather than heavy batteries

Continuous operations

- High power charging stops are integrated into routes
- No battery swapping, no extra fleet, no dwell time

Enhanced passenger comfort

- Elimination of unpleasant smell from gas fumes
- Less noise and vibration for a more enjoyable passenger journey

Lower Total Cost of Ownership (TCO)

- Reduction of the total cost of ownership, as well as lifecycle expenses
- No need to maintain two technologies compared with hybrids

primove automotive
eMobility unplugged

With virtually all electric devices now going wireless, it makes little sense to keep electric road vehicles tied to the leash in the form of charging plugs. Not only is plugging in the vehicle a real inconvenience but this type of system is also inherently unsuitable for energy transfer at very high power levels.

Moreover, several studies suggest that the key barriers preventing entry into the electric automotive market are fears about range constraints and the hassle associated with plug-in systems.

When it comes to commercial fleets, vehicle availability and service reliability are even more crucial to ensuring commercial success. This is why the PRIMOVE charging concept is designed around existing operations, ensuring continuous service for anything from delivery vans to taxis. With the opportunity charging approach coupled with high power transfer, the PRIMOVE system overcomes the key constraints, liberating electric fleets from range limitations with a charging process that is fast, convenient and safe.

Uninterrupted service

- Designed to ensure a continuous flow of fleet operations
- Minimised range and recharging constraints thanks to high power charging

Easy integration

- Prefabricated and tested modules are quickly integrated into any ground surface
- The system can be fitted onto any new or existing infrastructure

Lower maintenance and lifecycle costs

- Reduced total infrastructure costs and risk of vandalism
- No moving parts, no wear and tear

Driver-friendly

- No hassle with plugs, no special qualifications or training required
- No risk of human contact with electricity

Mannheim, Germany

A state-of-the-art eMobility facility

Committed to innovation and the continued development of PRIMOVE technology, Bombardier has opened a dedicated eMobility facility in Mannheim (Germany). This new Centre of Excellence supports partnerships, projects and opportunities in the fast-moving electric mobility sector. It hosts a complete power lab test set-up for all applications. Vehicles have been acquired to ensure that testing at the facility is conducted independently and in a real-life setting. Current tests are being performed on a minivan with a new prototype power receiver (pick-up) specifically designed for vehicles of this size. Further tests will help fine-tune and optimise the overall system and the functionality of individual components such as the cooling system, compatibility with external components and charging efficiency.

Facts & figures

Inauguration date:
September 2011

Number of vehicles tested:
1 bus, 2 minivans

Number of engineers:
50 highly-qualified employees

BOMBARDIER
100 years of experience in eMobility

As the global leader in the rail industry, Bombardier has over a century of experience in electric mobility. With 64 production and engineering sites in 26 countries, Bombardier Transportation develops, manufactures and services the broadest portfolio of mobility products in the world, making it the ideal partner for taking eMobility into the next phase of its evolution.

PRIMOVE technology is one of the highlights within the innovative BOMBARDIER ECO4 portfolio of technologies, which offer energy and cost-efficient solutions for total mobility performance.

Bombardier Transportation
Schöneberger Ufer 1
10785 Berlin, Germany

Phone +49 30 98607 0
Fax +49 30 98607 2000

www.primove.bombardier.com

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Learn more about our commitment to sustainable mobility on:
www.theclimateisrightfortrains.com

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BOMBARDIER
the evolution of mobility

primove
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No emissions
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e-mobility redefined

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Discover how the PRIMOVE solution is ready to transform the e-mobility landscape today.

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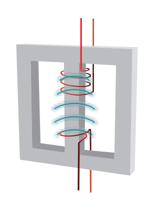
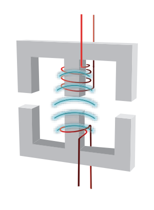


Electric current in a primary coil (winding) creates a magnetic field, which induces current in a secondary coil.



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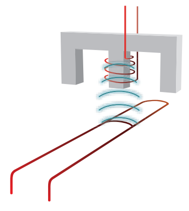

If the primary coil is extended in a loop, the secondary coil can receive power anywhere along this loop.

Introducing high power opportunity charging

Range and recharging constraints are the key concerns when it comes to converting an entire delivery fleet or bus network to electric power. In order to address these issues while offering a solution that is light, easy to integrate and competitive, the PRIMOVE system combines a regular charging pattern with energy transfer at high power levels. The charging process is seamlessly integrated into existing operations, thereby ensuring uninterrupted service without any need for additional fleet vehicles or batteries.

Light rail

Charging segments are integrated at every tram stop and the following few metres to enable recharging while letting passengers on/off and during acceleration.

Bus

Charging stations are positioned in the depot and/or en route at bus stops for recharging while letting passengers on/off without extended dwell times.

Automotive

Charging stations are installed at strategic points (e.g. loading docks for delivery vans, taxi ranks in airport waiting areas, supermarket parking spaces) to allow fast charging at convenient times when the vehicle is periodically not in use.

primove light rail
Liberating trams from overhead lines

In many ways, trams and light rail vehicles are the ultimate form of e-mobility. Yet despite being clean, silent and convenient, they have always been hampered by one disadvantage – catenaries. Catenary power systems are complex to install, demanding to maintain and clutter the urban space with unattractive infrastructure.

No compromise on performance

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Thanks to PRIMOVE contactless charging, light rail vehicles can now run without any need for unsightly poles and overhead lines. The energy source is moved underground and charges the vehicle via inductive power transfer. It now becomes possible to integrate light rail vehicles into urban areas where conventional catenary networks are prohibited or unwelcome – city centres, parks, gardens and protected heritage sites. The cityscape is left untouched, minimising visual pollution and improving the overall appeal of the city.

Minimised visual pollution

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- Installation is possible even in previously unsuitable areas such as heritage-protected sites

Reduced infrastructure

- Less land take needed than for catenary systems
- Less maintenance: no wear of pantographs and overhead lines, no risk of vandalism

Operational under all conditions

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- Compatible with all road surfaces and tracks

Augsburg, Germany

Demonstrating safe high power inductive charging for trams

In September 2010, Bombardier Transportation installed the contactless and catenary-free PRIMOVE system for trams on a 800-metre section of Line 3 to the Augsburg trade fair centre. The pilot project is being co-funded by the German Federal Ministry for Transport, Building and Urban Development (BMVBS) and realized in cooperation with the Augsburg Transport Authority (Stadtwerke Augsburg Verkehrs-GmbH) with the aim of demonstrating reliable operation under the real conditions of daily operation in an urban environment.

Federal Ministry
of Transport, Building
and Urban Development

Facts & figures

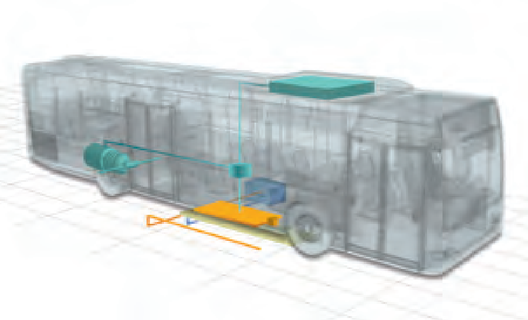
Start of operations:
September 2010

Vehicle type:
1 Bombardier bidirectional low-floor tram

Charging power:
200 kW

Braunschweig, Germany

Taking the primove concept to the road



Bombardier's first PRIMOVE bus project for passenger operation has been kicked off in the city of Braunschweig, Germany, which marks a significant leap forward in bringing clean e-mobility solutions to urban areas. A 12 km section of the bus network is turned into an eco-friendly electric route which is served by two PRIMOVE equipped buses. The German Federal Ministry of Transport, Building and Urban Development is granting Bombardier and its project partners, the public transport operator Braunschweiger Verkehrs-AG, the local energy company BS Energy, as well as the Technical University of Braunschweig, the sum of 2,9 million EUR to fund the initiative.

Federal Ministry
of Transport, Building
and Urban Development

Facts & figures

Start of operations:
Q3 2013

Vehicle type:
2 Solaris buses (12 m and 18 m)

Length of route:
12 km

primove bus
Going electric

The bus market is experimenting with alternatives to combustion-driven vehicles, but few of these approaches offer a sustainable solution to our dependence on fossil fuel. More often than not, they involve serious compromises in vehicle availability, service reliability, aesthetics, or resources (e.g. battery swapping, requiring extra fleet vehicles or turning to conductive charging). In essence, these solutions fail to address the key issue of making the electric bus market competitive and attractive.

PRIMOVE technology represents a major leap forward by offering a wireless charging system that is easy to install and convenient to use. By incorporating high power charging at the most convenient points along bus routes, the PRIMOVE system ensures optimum fleet availability. The wireless charging process is seamlessly integrated into existing operations to allow uninterrupted service without reverting to impractical, unattractive or unaffordable solutions.

Continuous operations

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Smaller, lighter system

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primove automotive
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Moreover, several studies suggest that the key barriers preventing entry into the electric automotive market are fears about range constraints and the hassle associated with plug-in systems.

When it comes to commercial fleets, vehicle availability and service reliability are even more crucial to ensuring commercial success. This is why the PRIMOVE charging concept is designed around existing operations, ensuring continuous service for anything from delivery vans to taxis. With the opportunity charging approach coupled with high power transfer, the PRIMOVE system overcomes the key constraints, liberating electric fleets from range limitations with a charging process that is fast, convenient and safe.

Uninterrupted service

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Easy integration

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Driver-friendly

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- No risk of human contact with electricity

Mannheim, Germany

A state-of-the-art e-mobility hub

Committed to innovation and the continued development of PRIMOVE technology, Bombardier has opened a dedicated e-mobility-facility in Mannheim, Germany. This Centre of Excellence supports partnerships, projects and opportunities in the fast-moving electric mobility sector. It hosts a complete power lab test set-up for all applications as well as a test hall for electric buses. Different vehicles including buses and minivans have been acquired to ensure that testing at the facility is conducted independently and in a real-life setting.

Facts & figures

Inauguration date:
September 2011

Applications tested:
Bus, minivan, car, tram

Number of engineers:
50 highly-qualified employees

BOMBARDIER
100 years of experience in e-mobility

As the global leader in the rail industry, Bombardier has over a century of experience in electric mobility. With 64 production and engineering sites in 26 countries, Bombardier Transportation develops, manufactures and services the broadest portfolio of mobility products in the world, making it the ideal partner for taking e-mobility into the next phase of its evolution.

PRIMOVE technology is one of the highlights within the innovative BOMBARDIER ECO4 portfolio of technologies, which offer energy and cost-efficient solutions for total mobility performance.

Bombardier Transportation
Schöneberger Ufer 1
10785 Berlin, Germany

Phone +49 30 98607 0
Fax +49 30 98607 2000

www.primove.bombardier.com

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Learn more about our commitment to sustainable mobility on:
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BOMBARDIER
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U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

DOT HS 811 574 **January 2012**

Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries

The National Highway Traffic Safety Administration (NHTSA) is committed to ensuring the highest standards of safety on our Nation's roadways. To better protect consumers and the public safety community from the potential risk of fire and other hazards related to vehicles that have been involved in a motor vehicle crash, NHTSA has developed "Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage (HV) Batteries." Developed with the assistance and expert input of the National Fire Protection Association, the Department of Energy (DOE) and others, the interim guidance for electric and hybrid-electric vehicles identifies appropriate post-crash safety measures for vehicle owners and the general public, emergency responders, and for towing/recovery operators and vehicle storage facilities.

NHTSA does not believe that electric vehicles present a greater risk of post-crash fire than gasoline-powered vehicles. In fact, all vehicles—both electric and gasoline-powered—have some risk of fire in the event of a serious crash. However, electric vehicles have specific attributes that should be made clear to consumers, the emergency response community, and tow truck operators and storage facilities. Out of an abundance of caution to prevent injury and loss of property, the interim guidance identifies considerations and actions for all electric and hybrid-electric vehicle crashes, including those involving the growing number of vehicles powered by lithium-ion batteries.

This interim guidance is intended to serve as a general reference for vehicle operators and responders. It was developed using current best practices and instructions from vehicle and battery manufacturers and others. It is not intended to replace information issued by the vehicle manufacturer, but rather to be used as a supplement to vehicle-specific guides. For more information about specific vehicle models, individuals should consult guidance provided by the vehicle manufacturer.

NHTSA, together with the Department of Energy, is continuing to explore strategies to ensure that the public and responder community receive the best information in the shortest possible time. The agency hope that this guidance will help to inform activities to educate responders and the public about electric vehicles including efforts already underway by DOE, NFPA, vehicle manufacturers, and others.

Interim Guidance for Electric and Hybrid-Electric Vehicles
Equipped With High Voltage Batteries
(Vehicle Owner/General Public)

ELECTRIC AND HYBRID-ELECTRIC VEHICLE CONSIDERATIONS

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires, and HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapors are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

VEHICLE INFORMATION

- Know the make and model of your vehicle.
- Review the owner's manual and become familiar with your vehicle's safety information and recommended safety practices.
- Do not attempt to repair damaged electric or hybrid-electric vehicles yourself. Contact an authorized service center or vehicle manufacturer representative for service.

EMERGENCIES

CRASH: A crash or impact significant enough to require an emergency response for conventional vehicles would also require the same response for electric or hybrid-electric vehicles.

If possible

- Move your car to a safe, nearby location and remain on the scene.
- Roll down windows before shutting the vehicle off.
- Place the vehicle in Park, set the parking brake, turn off the vehicle, activate hazard lights, and move keys at least 16 feet away from the vehicle.

Always

- Call 911 if assistance is needed and advise that an electric or hybrid-electric vehicle is involved.
- Do not touch exposed electrical components or the engine compartment, as a shock hazard may exist.
- Avoid contact with leaking fluids and gases, and remain out of the way of oncoming traffic until emergency responders arrive.
- When emergency responders arrive, tell them that the vehicle involved is an EV or HEV.

FIRE: As with any vehicle, call 911 immediately if you see sparks, smoke, or flames coming from the vehicle.

- Exit the vehicle immediately.
- Advise 911 that an electric or hybrid-electric vehicle is involved.
- As with any vehicle fire, do not inhale smoke, vapors, or gas from the vehicle, as they may be hazardous.
- Remain a safe distance upwind and uphill from the vehicle fire.
- Stay out of the roadway and stay out of the way of any oncoming traffic while awaiting the arrival of emergency responders.

POST-INCIDENT

- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure or within 50 feet of any structure or vehicle.
- Ensure that passenger and cargo compartment remain ventilated, i.e., open a window, door or trunk.
- Notify an authorized service center or vehicle manufacturer representative as soon as possible as there may be other steps they can take to secure and discharge the HV battery.
- Call 911 if you observe leaking fluids, sparks, smoke, flames, or hear gurgling or bubbling from the HV battery.

Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries (Law Enforcement)

ELECTRIC AND HYBRID-ELECTRIC VEHICLE CONSIDERATIONS

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires, and HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapors are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

IDENTIFY VEHICLE

Determine if the vehicle is an electric or hybrid-electric vehicle, and if it is, advise Dispatch and all responders that an electric or hybrid-electric vehicle is involved.

IMMOBILIZE VEHICLE

- Always approach vehicle from the sides to stay out of potential travel path. It may be difficult to determine if the vehicle is running due to lack of engine noise.
- If possible, chock the tires, place the vehicle into Park and set the parking brake.

DISABLE VEHICLE

- Place vehicle in Park, set parking brake, turn off the vehicle, activate hazard lights, and move vehicle keys at least 16 feet away from vehicle.
- If your local standard operating procedures (SOPs) allow, and if you are properly trained and equipped, disconnect the 12-volt battery. CAUTION: Safety restraints, air bags and other safety systems may be active for up to five minutes after disconnecting the 12-volt battery.

EMERGENCIES

NOTE: Follow local standard operating procedures (SOPs) for personal protection and safety.

CRASH:

- If you detect leaking fluids, sparks, smoke, flames, increased temperature, gurgling, popping or hissing noises from the HV battery compartment, ventilate passenger area (i.e., roll down windows or open doors) and request fire department response.
- Request Emergency Medical Services if there are injuries as a result of the crash.
- If you detect any unusual odors or experience eye, nose, or throat irritation, move away from the vehicle and evacuate others from the immediate area.
- Avoid contact with orange high voltage cabling and areas identified as high voltage risk by warning labels.
- Remain a safe distance upwind and uphill from the vehicle and stay out of the way of oncoming traffic until other appropriately equipped emergency responders arrive.
- Be alert. There is a potential for delayed fire with damaged lithium-ion batteries.

FIRE:

- If you are unable to quickly remove the occupants, use a fire extinguisher to protect them from the flames.
- As with any vehicle fire, the byproducts of combustion can be toxic and all individuals should be directed to move to a safe distance upwind and uphill from the vehicle fire and out of the way of oncoming traffic.

POST-INCIDENT

- Always assume the HV battery and associated components are energized and fully charged during investigation and storage.
- Ensure that passenger and cargo compartment remain ventilated, i.e., open window, door, or trunk during investigation and storage.
- Notify an authorized service center or vehicle manufacturer representative as soon as possible as there may be other steps they can take to secure and discharge the HV battery.
- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure or within 50 feet of any structure or vehicle.
- Request fire department if you observe leaking fluids, sparks, smoke, flames, or hear gurgling or bubbling from the HV battery.

Interim Guidance for Electric and Hybrid-Electric Vehicles
Equipped With High Voltage Batteries
(Emergency Medical Services)

ELECTRIC AND HYBRID-ELECTRIC VEHICLE CONSIDERATIONS

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires or HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapors are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

IDENTIFY VEHICLE

Determine if the vehicle is an electric or hybrid-electric vehicle, and if it is, advise Dispatch and all responders that an electric or hybrid-electric vehicle is involved.

IMMOBILIZE VEHICLE

- Always approach vehicle from the sides to stay out of potential travel path. It may be difficult to determine if the vehicle is on due to lack of engine noise.
- If possible, chock the tires, place the vehicle into Park and set the parking brake.

DISABLE VEHICLE

- Place vehicle in Park, set parking brake, turn off the vehicle, activate hazard lights, and move vehicle keys at least 16 feet away from the vehicle.
- If your local standard operating procedures (SOPs) allow and if you are properly trained and equipped, disconnect the 12-volt battery. CAUTION: Safety restraints, air bags, and other safety systems may be active for up to five minutes after disconnecting 12-volt battery.

EMERGENCIES

NOTE: Follow local standard operating procedures (SOPs) for personal protection and safety

CRASH:

- Request law enforcement response if you need assistance with traffic control or scene safety.
- If you detect leaking fluids, sparks, smoke, flames, increased temperature, gurgling, popping or hissing noises from the HV battery compartment, ventilate passenger area (i.e., roll down windows or open doors) and request fire department response.
- Avoid contact with orange high voltage cabling and areas identified as high voltage risk by warning labels.

- Move away from the vehicle and evacuate others from the immediate area if you detect any unusual odors or experience eye, nose, or throat irritation. Rapid extrication may be needed for injured or trapped occupants.
- Remain a safe distance upwind and uphill from the vehicle and out of the way of oncoming traffic until other appropriately equipped emergency responders arrive.
- Be alert. There is a potential for delayed fire with damaged lithium-ion batteries.

FIRE:

- If you are unable to quickly remove the occupants, use a fire extinguisher to protect them from the flames.
- As with any vehicle fire, the byproducts of combustion can be toxic and all individuals should be directed a safe distance upwind and uphill from the vehicle fire and out of the way of oncoming traffic.

POST-INCIDENT

- Always assume the HV battery and associated components are energized and fully charged.
- Ensure that passenger and cargo compartment remain ventilated, i.e., open window, door, or trunk if and when inside vehicle providing patient care.
- Notify authorized service center or vehicle manufacturer representative as soon as possible as there may be other steps they can take to secure and discharge the HV battery.
- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure or within 50 feet of any structure or vehicle.
- Request fire department if you observe leaking fluids, sparks, smoke, flames, or hear gurgling or bubbling from the HV battery.

Interim Guidance for Electric and Hybrid-Electric Vehicles
Equipped With High Voltage Batteries
(Fire Department)

ELECTRIC AND HYBRID-ELECTRIC VEHICLE CONSIDERATIONS

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires, and HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapors are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

IDENTIFY VEHICLE

- Determine if the vehicle is an electric or hybrid-electric vehicle, and if it is, advise Dispatch and all responders that an electric or hybrid-electric vehicle is involved.

IMMOBILIZE VEHICLE

- Always approach vehicle from the sides to stay out of potential travel path. It may be difficult to determine if the vehicle is running due to lack of engine noise.
- If possible, chock the tires, place the vehicle into Park, and set the parking brake.

DISABLE VEHICLE

- Place vehicle in Park, set parking brake, turn off the vehicle, activate hazard lights, and move vehicle keys at least 16 feet away from vehicle.
- If your local standard operating procedures (SOPs) allow and if you are properly trained and equipped, disconnect the 12-volt battery. CAUTION: Safety restraints, air bags, and other safety systems may be active for up to five minutes after disconnecting the 12-volt battery.

EMERGENCIES

NOTE: Follow local standard operating procedures (SOPs) for personal protection and safety

CRASH:

- If you detect leaking fluids, sparks, smoke, flames, increased temperature, gurgling or bubbling sounds from the HV battery compartment, assume there is a battery fire and ventilate the passenger area (i.e., roll down windows, or open doors).
- If there is fire, and occupants are still inside the vehicle or are trapped, use a fire extinguisher to protect the occupants until a hose line is available or until the occupants are removed.

- Request Emergency Medical Services if there are injuries as a result of the crash.
- Request law enforcement if you need assistance with traffic control or scene safety.
- Move away from the vehicle and evacuate others from the immediate area if you detect any unusual odors or experience eye, nose, or throat irritation. Wear full Personal Protective Equipment (PPE) and Self-Contained Breathing Apparatus (SCBA) if rapid extrication is necessary for injured or trapped occupants.
- Be alert. There is a potential for delayed fire with damaged lithium-ion batteries.

FIRE:

NOTE: If the fire involves a lithium-ion battery, it will require large, sustained volumes of water for extinguishment. If there is no immediate threat to life or property, consider defensive tactics and allow fire to burn out.

- If there is active fire, follow local SOP for vehicle fires. Wear appropriate Personal Protective Equipment (PPE) and Self Contained Breathing Apparatus (SCBA) at all times.
- If occupants are still inside the vehicle or are trapped, use a fire extinguisher to protect the occupants until a hose line is available or until the occupants are removed.
- Establish a safe perimeter around the vehicle.
- Consider establishing a water supply to support long-term operation.
- Use a hose line to apply water to extinguish the fire while continuing to cool the HV battery and its casing. Never attempt to penetrate the HV battery or its casing to apply water.
- Avoid contact with orange high voltage cabling and areas identified as high voltage risk by warning labels.
- Be alert. There is a potential for delayed ignition or re-ignition of a lithium-ion battery fire even after it is believed to be extinguished. This may remain an issue until the lithium-ion battery is properly discharged.
- As with any vehicle fire, the byproducts of combustion can be toxic and all individuals not properly trained, dressed, and equipped to fight the fire should be directed a safe distance upwind and uphill from the vehicle fire and out of the way of oncoming traffic.

POST-INCIDENT

- Always assume the HV battery and associated components are energized and fully charged.
- Ensure that passenger and cargo compartments remain ventilated, i.e., open window, door or trunk if and when inside vehicle providing patient care.
- Notify an authorized service center or vehicle manufacturer representative (dealer) as soon as possible as there may be additional steps they can take to secure and discharge the HV battery.
- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure or within 50 feet of any structure or vehicle.
- Vehicle should be monitored for leaking fluids, sparks, smoke, flames, gurgling or bubbling sounds from the HV battery, and if detected, assume the HV battery is burning and follow above guidance to extinguish the fire.

Interim Guidance for Electric and Hybrid Vehicles
Equipped With High Voltage Batteries
(Towing and Recovery Operators and Vehicle Storage Facilities)

ELECTRIC AND HYBRID-ELECTRIC VEHICLE CONSIDERATIONS

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires, and HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapors are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

IDENTIFY VEHICLE

- Determine if the vehicle is an electric or hybrid-electric vehicle, and if it is, advise your Dispatch and all other responders that an electric or hybrid-electric vehicle is involved.
- If you detect leaking fluids, sparks, smoke, flames, increased temperature, gurgling, popping or hissing noises from the HV battery compartment, ventilate passenger area (i.e., roll down windows or open doors) and call 911.
- Be alert. There is a potential for delayed fire with damaged lithium-ion batteries.

RECOVERING /TRANSPORTING VEHICLE:

- **Call an authorized service center or vehicle manufacturer representative, if necessary, to determine additional steps that you should take to safely recover or transport the vehicle.**
- Always approach vehicle from the sides to stay out of potential travel path. It may be difficult to determine if the vehicle is running due to lack of engine noise.
- Place vehicle into Park, set parking brake, turn off the vehicle, activate hazard lights, and remove keys to a distance at least 16 feet away from the vehicle until loading vehicle for transport.
- Refer to vehicle manual/recovery guide to locate proper attachment/connection points and transport method.
- Avoid contact with orange high voltage cabling and areas identified as high voltage risk by warning labels.

STORING VEHICLE

- **Notify authorized service center or vehicle manufacturer representative as soon as possible as there may be additional steps necessary you or they can take to secure and, discharge, handle, and store the HV battery and vehicle.**
- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure or within 50 feet of any structure or vehicle.
- Ensure that passenger and cargo compartments remain ventilated.
- Prior to placing and while located in storage area/tow lot, continue to inspect vehicle for leaking fluids, sparks, smoke, flames, gurgling or bubbling sounds from the HV battery and call 911 if any of these are detected.
- Maintain clear access to stored vehicles for monitoring and emergency response if needed.

Resource Guide

The National Highway Traffic Safety Administration is dedicated to achieving the highest standards of excellence in motor vehicle and highway safety. NHTSA provides the public with facts on vehicle safety, driving safety, and research.
www.nhtsa.gov
www.safercar.gov
www.ems.gov

Electric Vehicle Safety Training is a nationwide program through the National Fire Protection Association to help firefighters and other first responders effectively deal with emergency situations involving electric and hybrid-electric vehicles. The Web site hosts an EV blog, calendar of events, training videos, emergency field guides from 19 auto manufacturers, research reports, as well as an online training course for the Chevy Volt.
www.evsafetytraining.org

SAE International is a resource for vehicle safety codes and standards. It has recently developed and revised safety standards for electric vehicles.
www.sae.org/standards

The Electric Drive Transportation Association is a resource for learning about different types of hybrid-electric and electric vehicles. It also has a fact sheet that details the numbers of hybrid vehicles on the road now and how many we can expect in the future.
www.electricdrive.org

The Alternative Fuels and Advanced Vehicles Data Center provides information, data, and tools to help fleets and other transportation decision-makers find ways to reduce petroleum consumption through the use of alternative and renewable fuels, advanced vehicles, and other fuel-saving measures.
www.afdc.energy.gov/afdc

HybridCars has detailed resources on every hybrid model on the road today. Its research section also provides studies and surveys about hybrid and electric vehicles in relation to technology, the environment, culture, and law.
www.hybridcars.com

The National Alternative Fuels Training Consortium promotes programs and activities that lead to energy independence, and encourages the greater use of cleaner transportation.
www.naftc.wvu.edu

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January 2012

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

NHTSA
www.nhtsa.gov

National Fire Protection Association
The authority on fire, electrical, and building safety

COVER STORY

Elemental Questions

As lithium-ion battery use increases, so do the concerns related to the fire-safety hazards of these devices. Through a series of research efforts and partnerships, NFPA is analyzing storage and safety issues surrounding the power source fueling hundreds of millions of devices — from iPhones to electric vehicles — worldwide.

NFPA Journal®, *March/April 2012*

By Fred Durso, Jr.

On a November evening in 2009, residents of Trail, British Columbia, were jolted by explosions that some people thought were part of a fireworks display. The bursts were actually the result of a fire at nearby Toxco Inc., a battery recycling facility. The explosions intensified as the fire ripped through the battery discharge building, and flaming projectiles from a bunker filled with "primary" lithium batteries caused the fire to spread to the adjoining district recycling facility.

The Canadian Broadcasting Corporation reported that the fire was so intense that firefighters could only attempt to contain the blaze for several hours before letting it burn out; lithium is highly reactive to water, and it was feared that attempts to douse the flames might have intensified the blaze. While there were no injuries or deaths, the fire destroyed the battery discharge building. A cause was never identified, but officials speculated that the fire was the result of an internal short in one of the stored batteries.

Incidents like the Toxco fire underscore the flammability and combustibility hazards associated with lithium batteries, which encompass dozens of different chemistries using pure lithium metal or lithium compounds-from the non-rechargeable primary lithium batteries used in industrial applications to the rechargeable lithium-ion cells that power our cameras, mobile phones, and even electric vehicles. Their range of uses is fueling their growing popularity; market projections indicate that the use of lithium-ion batteries, for example, is growing at about 20 percent per year.

YOUTUBE VIDEO INTERVIEW

Senior project manager Andrew Klock gives some insight into the National Highway Traffic Safety Administration's new electric vehicle guidelines and how they can help emergency responders.

Cabot, a global performance materials company, reports that battery makers sold about $8 billion of lithium-ion batteries globally last year. By 2020, Cabot says, that number is expected to increase to more than $18 billion. Concerns related to the protection of large quantities of lithium-ion batteries in storage settings against potential fires are expected to rise as more technologies embrace this popular power source.

Among the many industries looking to this emerging power source is the auto industry, which has incorporated lithium technology into its latest crop of electric vehicles (EVs). President Barack Obama has pledged to have a million EVs on U.S. roadways by 2015, a goal supported by U.S. Department of Energy Secretary Steven Chu, who recently said the country has a "good shot" of attaining this target. But the rechargeable lithium-ion battery technology used in these vehicles recently came under scrutiny when a Chevrolet Volt caught fire weeks after a crash test performed as part of a new-vehicle evaluation by the National Highway Traffic Safety Administration (NHTSA). The incident prompted an NHTSA investigation as well as a congressional hearing, where politicians grilled NHTSA and General Motors officials on the vehicle's safety, as well as on the timing of the NHTSA study. (For more on the NHTSA study, see “Crash + Burn.")

As dialogue on battery safety continues, NFPA is working with government agencies, insurers, and car manufacturers to address a national issue of emergency responder and consumer safety, and is offering its input and expertise to address the potential risks. The Fire Protection Research Foundation has initiated a study to identify the hazards, research gaps, and best suppression methods for batteries in storage settings. NFPA's Electric Vehicle Safety Training Project continues to educate the emergency responder and law enforcement communities on the safe handling of these batteries. Staff members have worked with NHTSA to develop guidelines for emergency responders on handling fires involving EVs and hybrid-electric vehicles.

"NFPA is uniquely situated to assist NHTSA and America's responders in looking at the challenges posed by the next generation of vehicles," says Ken Willette, NFPA division manager of Public Fire Protection. "We can draw from our technical expertise to provide best practices when responding to incidents involving these cars. If you add the Foundation's efforts in examining lithium-ion battery storage practices and extinguishing fires involving these battery packs, NFPA was the right choice to support NHTSA's work."

The storage challenge

Much of the current research and safety activity is aimed at lithium-ion batteries, which pack more energy per volume than other rechargeable battery chemistries and are in part responsible for lighter and sleeker designs for consumer electronics. (See “Staying Energized” for a primer on the science of lithium-ion batteries.) The appeal of this battery type extends beyond its size and power, since these power sources are able to maintain the bulk of their charge for months at a time when not in use and typically require minimal maintenance.

SIDEBARS

Crash + Burn

How a puzzling after-the-fact fire launched an investigation of the Chevrolet Volt’s lithium-ion battery.

French Connection

Upcoming seminar underscores global impact of European research on lithium-ion batteries.

Staying Energized

A primer on the science fueling the lithium-ion battery market.

But the technology also comes with its own hazards. Late last year, retailer Best Buy and the Consumer Product Safety Commission recalled battery cases made for specific Apple iPhones following incidents of batteries overheating that burned more than a dozen users. In a very different application of the technology, tests on the lithium-ion battery packs in the Chevrolet Volt-General Motors' EV that also relies on a gasoline generator for power once the battery pack is discharged-also resulted in fires, though no incidents of Volt fires on roadways have been documented.

Addressing the potential fire hazards related to this technology, the Fire Protection Research Foundation's Property Insurance Research Group (PIRG) initiated the Lithium-Ion Battery Storage Protection Project last year to address potential fire risks involving these batteries in bulk storage and distribution settings. "What we're seeing is an emerging issue," says Richard Gallagher, line of business director-property for Zurich Services Corporation Risk Engineering and a PIRG member. "We realized that we're going to see warehouses filled with these batteries, but we really don't know how to protect them. Nowhere is there guidance to direct a building owner on how to protect this commodity."

The project's first phase was a literature review commissioned last year by the Foundation that identified these gaps in fire protection and assessed battery hazards. Among the hazard issues addressed in the final report, Lithium-Ion Batteries Hazard and Use Assessment, was the battery's makeup, particularly its high energy density and flammable solvent that aids ion movement in battery cells during charging. The report also identified the rare, yet potentially dangerous, circumstances leading to battery failure, including poor cell design or defects leading to short circuits, cell manufacturing flaws, external abuse of cells, and charging inadequacies. The rapid self-heating of a cell, known as "thermal runaway," is what the report terms an "energetic failure" that may cause the electrolyte to combust, potentially leading to a fire spreading to other battery cells or venting of potentially flammable vapors.

While there have been numerous studies conducted on small quantities of cells and small battery packs, little is known about the fire hazards of thermal runaway reactions, how these batteries burn in large quantities, or what suppression tactics are most effective. "This is a commodity that's become ubiquitous, and the fact that it's become ubiquitous before we've resolved these kinds of issues tell how well [lithium-ion batteries] work," says Celina Mikolajczak, senior managing engineer with Exponent, the engineering and scientific consulting firm that developed the research report for the Foundation. "They have been in the marketplace for about 20 years, originally in small volumes. As more cells are being shipped and more people use them, we certainly want to be aware of the associated risks, especially as bigger batteries are developed and we contemplate greener technologies."

PIRG met last August at the Foundation's Lithium-Ion Battery Storage Hazard Assessment Workshop in Baltimore to discuss findings from the Foundation's report and remaining gaps in fire hazard and suppression research. The workshop's "general battery storage" subgroup agreed that full-scale fire tests in these settings would determine the appropriate containment methods.

Heeding this advice, PIRG will begin testing this year as part of the second phase of its research project, which also includes determining the appropriate fire protection commodity classification for lithium-ion batteries. Exponent has already identified various commodity types and their challenges relative to bulk storage protection. PIRG has condensed its research list to two particular commodity types: small-format battery packs, and cells packed in large modules that when combined form EV batteries. PIRG will share the commodity classifications and testing results with NFPA 13, Installation of Sprinkler Systems, technical committees in order to aid the development of provisions related to lithium-ion battery storage. "Once the nature of the commodity is understood, the next step is to identify compatible fire extinguishing agents and design guidelines that the NFPA 13 committees can use to fill the current voids," says Gallagher.

The EV challenge

Lithium-ion car batteries received their fair share of attention over the past year. NHTSA, which occasionally assesses vehicles that incorporate new technology, initiated a series of tests on EVs last year. According to the agency's Chevrolet Volt Battery Incident Overview Report published in January, a crash test in May involving the Volt resulted in the leakage of battery coolant, damage to some of the battery's cells, and an electric short that precipitated a fire three weeks after the crash. During another round of tests in November, batteries began to smoke and emit sparks, while another caught fire a week after the tests.

While NHTSA isn't aware of any roadway crashes resulting in EV battery fires, it opened a defect investigation on the Volt in late November to further analyze the findings. A month later, GM proposed several modifications to the Volt, including the strengthening of the car's structure to further protect the battery pack during a collision and the addition of a sensor to monitor battery coolant levels. The upgrades will be applied to vehicles in production, as well as to the more than 8,000 Volts already on the road.

Also in November, NHTSA contacted NFPA to help assemble a series of interim guidelines for emergency responders, tow truck operators, consumers, and storage facilities to consider in the event of an EV or hybrid-electric vehicle fire. Staff members and consultants with NFPA's Electric Vehicle Safety Training Project and Public Fire Protection Division, who are well versed on handling various hazardous materials and response procedures, collaborated for the new project. NFPA is incorporating the interim guidelines into its EV training project, which instructs emergency responders on the growing fleet of EVs and related hazards through a series of online and classroom trainings.

"I'd compare NFPA's role in developing the interim guidelines to a fire ground commander calling in a specialty team to assist with a challenging situation," says NFPA's Willette. "NHSTA called us to provide technical guidance and insight into the development of the interim guidelines. The NFPA team responded, with all members focusing on their tasks until the mission was accomplished." With that input, Willette says, NHSTA was able to draft the interim guidelines.

Following the creation of the guidelines and structural safeguards for the Volt, NHTSA concluded its investigation in January. "NHTSA does not believe that the Chevy Volt or other electric vehicles pose a greater risk of fire than gasoline-powered vehicles," the agency said in a statement. (NFPA statistics indicate that in 2010 there were roughly 184,000 highway vehicle fires, nearly all of them in gasoline-powered vehicles, which resulted in 285 deaths.) "The agency expects this guidance will help inform the ongoing work by NFPA, the Department of Energy, and vehicle manufacturers to educate the emergency response community, law enforcement officers, and others about electric vehicles."

The manner in which NHTSA responded to the series of fires involving the Volt perplexed some politicians. A subcommittee of the House Oversight and Government Reform Committee held a hearing in January with NHTSA Administrator David Strickland, along with Dan Akerson, General Motor's chairman and chief executive officer, to question NHTSA on why it waited six months after the initial battery fire to launch an official investigation. The proceedings were at times acrimonious. "Your agency dropped the ball on this," U.S. Rep. Mike Kelly, a Pennsylvania Republican and committee member, said to Strickland at the hearing, according to the Grand Rapids Press. "For me, it comes down to taxpayer dollars being used to subsidize a product that this administration wants to go forward."

Strickland acknowledged the safety of the Volt and pointed out that there had been no on-the-road incidences of battery fires. He also testified that engineers used that time to meticulously analyze the cause of the fires. Had there been a public safety concern, Strickland said, NHTSA would have brought the issue to light sooner.

Gregory Cade, NFPA division director of Government Affairs, attended the hearing and noted that both Strickland and Akerson complimented NFPA for its involvement in developing the interim guidelines and on its collaboration with GM on aspects of NFPA's Electric Vehicle Safety Training Project. "The dilemma is that GM is only one carmaker using one battery technology," says Cade. "We've got to continue to reach out to other car and battery manufacturers. They're not all using the same technology."

NFPA has also continued expanding its EV training to other interested parties. The Department of Energy, which had initially awarded NFPA a $4.4 million grant in 2010 for its EV training project, recently extended participation to EMS and law enforcement officials. More than 15,000 people have already registered for an online training course featuring electrical and safety information on the Volt.

The course complements the project's "train the trainer" classroom courses attended by about 800 fire service professionals in 20 states. Anticipated for release this year is a reference guide that instructs emergency responders on identifying all makes and models of hybrid cars and EVs as well as how to safely respond to the vehicles in an emergency.

The training developments underscore NFPA's role as the authority on EV battery safety, says Andrew Klock, senior project manager for the EV Safety Training Project. "The training is exceeding our expectations," he says. "The attendance across the country has been much better than we anticipated. We thought we would have 45 fire service trainers in each state taking the course. In many states, we're pushing over 100. The EV Safety Training Project website is also becoming the place where the emergency responder community is getting their hybrid and EV safety information."

Looking ahead, the Foundation is partnering with the automotive industry and the Department of Energy (DOE) this year to develop best practices for the safe handling and disposal of damaged automotive batteries by emergency responders. The project is yet another aspect of the larger effort to assess and address the fire protection strategies of this rapidly emerging technology.

"EV battery safety represents a special challenge as this technology is in a rapid state of evolution," says Kathleen Almand, the Foundation's executive director. "Both NFPA and the Foundation have been proactively addressing many new energy-related technologies, from solar panels, to biofuel safety, to electric safety aspects of plug-in EVs to ensure that NFPA standards are appropriately addressing all of these emerging issues."

Fred Durso, Jr. is staff writer for NFPA Journal.

SIDEBAR

Crash + Burn

How a puzzling after-the-fact fire launched an investigation of the Chevrolet Volt’s lithium-ion battery

The following is adapted from NHTSA’s “Chevrolet Volt Battery Incident Overview Report.”

As part of its New Car Assessment Program (NCAP), NHTSA conducted four side-pole crash tests of the Chevrolet Volt in 2011 to evaluate the vehicle’s crashworthiness and occupant protection. All of the tested vehicles met compliance test requirements and were favorably rated for the NCAP program. Based on its performance, the Volt received an NHTSA five-star rating for both frontal and side-impact vehicle crashworthiness and occupant protection.

An EV battery damaged in a crash test started a fire that destroyed four vehicles at a test facility in Wisconsin. (Photo: NHSTA)

A side-pole crash test of a Chevrolet Volt was conducted on May 12, 2011, at MGA Research, a test facility in Wisconsin. On June 6, 2011, MGA Research personnel notified NHTSA that a fire event had occurred over the previous weekend and had been discovered by laboratory staffers that morning. The laboratory provided details of the vehicles involved in the event, which included the Chevrolet Volt that had been subjected to an NCAP pole test three weeks earlier.

After informing NHTSA about the fire, MGA notified the local fire authorities, who performed an initial scene investigation that focused on identifying possible arson issues. NHTSA contracted with a battery and fire expert, Hughes Associates, to investigate the origin and cause of the fire. The initial forensic inspection was conducted June 13–14 at the MGA facility. In

July 2011, Hughes Associates' preliminary findings indicated that the fire incident at MGA most likely originated in the Chevrolet Volt.

This preliminary finding triggered further investigation. The vehicle, along with the fire-damaged lithium-ion propulsion battery, was shipped to NHTSA's Vehicle Research and Test Center in East Liberty, Ohio. Hughes Associates, NHTSA, and General Motors (GM) representatives conducted a forensic inspection and battery teardown. The inspection of the crash damage to the Volt revealed that the transverse stiffener located under the driver's seat had penetrated the tunnel section of the battery compartment, damaged the lithium-ion battery, and ruptured the battery's liquid cooling system. Review of the crash test photographs and video confirmed that coolant had leaked from the battery compartment. Hughes Associates concluded that damage to some of the Volt's battery pack cells and electric shorting precipitated the fire.

In September 2011, NHTSA performed a fifth side-pole NCAP crash test on a Chevrolet Volt at the MGA facility. The objective was to observe any battery cell damage, shorting, battery coolant system rupture, or post-crash battery fire. The test vehicle was fitted with additional cameras and equipment to monitor post-crash events. This test resulted in no intrusion into the battery compartment, no cell damage or shorting, no leakage of coolant, and no post-impact fire. The vehicle was monitored for three weeks after the crash.

Six additional tests were performed on Volt lithium-ion battery packs to isolate potential factors involved in the MGA vehicle fire. Of the six tests, two batteries caught fire — one six days after the test, the other a week after testing. Another experienced a short arcing event with sparks and flames, one battery showed signs of heating at the connector, and another battery showed no test-related activity other than a slow discharge of one cell group. The sixth battery was inadvertently consumed by one of the batteries that caught fire. Despite the fires, NHTSA was unable to replicate the specifics of the MGA fire event in either the battery component testing or the full-scale vehicle tests and is not aware of any real-world post-crash fires involving an EV battery cell venting event.

In November 2011, NHTSA opened a defect investigation on the Chevrolet Volt. GM proposed a potential change (field fix) to mitigate intrusion of the transverse stiffener into the battery. NHTSA observed the installation of the proposed reinforcement into a 2012 production Chevrolet Volt, and the vehicle was shipped to MGA Research where an NCAP-style side-pole test was performed in December. The vehicle was monitored for three weeks. There was no intrusion into the battery compartment, no leakage of coolant, and no post-impact fire observed.

In November 2011, NHTSA also began working with NFPA to assist first and second responders in identifying vehicles powered by lithium-ion and other lithium-type batteries in taking appropriate steps in handling these batteries following a crash. NHTSA has also been working with vehicle manufacturers to develop appropriate post-crash protocols for dealing with lithium-ion battery powered vehicles.

SIDEBAR

French Connection

Upcoming seminar underscores global impact of European research on lithium-ion batteries

To truly understand the hazardous nature of lithium-ion batteries, and to develop corresponding safety measures against potential threats, the batteries must undergo a series of destructive tests.

Used lithium-ion cell phone batteries in a recycling facility. (Photo: AP/Wide World)

That's what's occurring inside the STEEVE — the English-language acronym translates to Electrochemical Energy Storage for Electric Vehicles — research facility in Verneuil-en-Halatte, France, where researchers damage these devices through crashes, fires, and electrical malfunctions.

In operation since 2010, the testing facility's sole purpose is to examine the ramifications of battery abuse. The French National Institute for Industrial Environment and Risks (INERIS), which addresses risks impacting life and property safety through studies and research programs, developed STEEVE in order to take a close look at lithium-ion batteries and to try to determine what has led to a smattering of international battery fires. Its latest research will be discussed during the High Challenge Storage Protection Seminar in Paris on June 27. Presented by the Fire Protection Research Foundation, the seminar addresses high-hazard commodities in storage settings and new approaches to fire protection.

While INERIS has yet to initiate research on lithium-ion batteries in storage settings, it has begun researching the life cycle of these devices and has identified potential hazardous scenarios along the way. The session at the Foundation seminar will identify the scenarios, including possible incidents involving the toxic components of these batteries, and prevention measures that optimize building protection.

"In a [battery] recycling plant, you'll never know the state of health of the batteries," says Guy Marlair, technical advisor and research scientist with INERIS. "They may be very close to the thermal runaway process [rapid self-heating of battery cells], or very far from that. It's difficult to have a clear idea. The way you will develop prevention and protection measures in a recycling facility will have to be different than warehouses storing new cells and batteries."

A technical panelist for the Foundation's Lithium-Ion Battery Storage Protection Project, Marlair says he plans to share current and future research findings for the good of the project. "This project is quite timely," he says. "We have to consolidate the research effort. We should concentrate on collecting all pieces of new information to achieve a satisfactory level of safety for the storage of these batteries. All of these different types of defects will need to be analyzed to ensure protection."

For more information on the Research Foundation's High Challenge Storage Protection Seminar, visit nfpa.org/foundation.

— Fred Durso, Jr.

SIDEBAR

Staying Energized

A primer on the science fueling the lithium-ion battery market

A lithium-ion battery's ability to provide considerable amounts of energy using lighter materials than its competitors has made this technology a popular option for consumer electronics and the growing electric vehicle industry. Here's a simplified look at the science responsible for powering many of today's gadgets.

Salar de Uyuni, in Bolivia, holds the world's largest reserve of lithium. (Photo: Corbis)

Lithium in its purest form — a silvery-white metallic element — is not found in lithium-ion cells. Rather, a chemical compound containing lithium (in some cases, lithium cobalt oxide) is used. The term "lithium-ion" refers to the positively charged atoms responsible for the battery's charging and discharging. A lithium-ion battery's metallic case contains a lithium-ion cell consisting of anodes (negative electrodes) that are commonly composed of lightweight elements, such as carbon, and cathodes (positive electrodes), a ceramic material made from the lithium cobalt oxide or other materials. The cathodes and anodes are placed onto individual copper or aluminum foils, separated by a porous piece of film, and submerged in an organic solvent known as an electrolyte. As the battery charges, the electrolyte aids the lithium ions (charged atoms created by the lithium salt in the electrolyte) that move through the film from the cathode to the anode. The direction of the ions is reversed during discharge, creating a flow of an electrical current. The batteries produce a higher voltage and can be recharged for hundreds of cycles, making these devices an increasingly popular power source. Cell phones, for example, use single-cell lithium-ion batteries, while notebook computers and other larger devices use multi-cell batteries.

Since lithium-ion batteries are sensitive to extreme temperatures, the battery pack or individual cell typically have a range of overcharge protection devices. Whereas comparable battery technologies use a water-based solvent as its electrolyte, lithium-ion batteries use a flammable solvent to perpetuate ion movement. Research has indicated that the device's high energy density and flammable solvent pose risks and challenges related to the storage and handling of these batteries.

— Fred Durso, Jr.

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BBC NEWS
BUSINESS

15 February 2013 Last updated at 11:15 ET

Airbus A350 to avoid Boeing 787-style lithium-ion batteries

Airbus says it will not use lithium-ion batteries in its forthcoming A350 plane because of problems that have grounded rival Boeing's 787 Dreamliner.

The European planemaker said it would use traditional nickel-cadmium batteries instead, as already used in the A380 and other models.

Investigations are continuing after battery problems came to light on 787s operated by Japan's top two airlines.

Airbus said they remained "unexplained to the best of our knowledge".

The firm said it did not expect any further delays to the launch of the A350. The maiden flight is due to take place later this year, with the first passenger flight expected in the second half of 2014.

In a statement, Airbus said it was "confident" that the lithium-ion battery that it had been developing with French battery-maker Saft was "robust and safe".

It added that A350 test flights would continue with the lithium batteries.

"However, to date, the root causes of the two recent industry Li-ion main batteries incidents remain unexplained to the best of our knowledge," Airbus said.

"In this context, and with a view to ensuring the highest level of programme certainty, Airbus has decided to activate its Plan B and therefore to revert back to the proven and mastered nickel-cadmium main batteries for its A350 XWB programme at entry into service (EIS).

"Airbus considers this to be the most appropriate way forward in the interest of programme execution and A350 XWB reliability."

The A350 is intended as a rival to the Dreamliner, which was grounded last month after a lithium-ion battery on a Japan Airlines plane caught fire, while an All Nippon Airways flight was forced to make an emergency landing because of a battery malfunction.

These planes use lithium-ion batteries because they are relatively powerful compared to their size and weight. They are used for significant functions such as providing the starting and emergency power supply on the A350 aircraft.

Lithium batteries are also commonly used in other planes, but these are much smaller batteries, running much more minor things such as a small set of lights.

Shares in battery-maker Saft fell after the announcement. When it agreed the Airbus contract in 2008, it said it expected it to be worth 200m euros ($267m; £172m) over 25 years.

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Boeing proposes full 787 battery fix to FAA: sources

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By Andrea Shalal-Esa and Alwyn Scott

WASHINGTON/SEATTLE | Fri Feb 22, 2013 6:54pm EST

(Reuters) - Boeing Co on Friday gave U.S. aviation regulators its plan to fix the volatile battery aboard its new 787 Dreamliner, even though investigators have not yet determined what caused the batteries to overheat on two planes last month.

Boeing did not propose abandoning the lithium-ion batteries and is not working on a backup or longer-term fix for the problem that has grounded its entire fleet of 50 Dreamliners for nearly five weeks, three sources familiar with the plan said.

The company and the U.S. Federal Aviation Administration said no firm result emerged from the meeting between Deputy Transportation Secretary John Porcari, FAA Administrator Michael Huerta and other FAA officials and Boeing Commercial Airplanes CEO Ray Conner and other senior Boeing executives in Washington.

With Boeing's costs mounting by millions of dollars a day while the planes are on the ground, the FAA said it is "reviewing a Boeing proposal and will analyze it closely. The safety of the flying public is our top priority and we won't allow the 787 to return to commercial service until we're confident that any proposed solution has addressed the battery failure risks."

Boeing declined to comment on the details of its proposal, but said the meeting with the FAA was productive.

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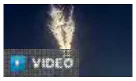
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The proposal to the FAA includes measures to address a range of possible causes of short-circuits in the batteries, the sources said.

Five weeks ago, U.S. authorities grounded the worldwide fleet of 787s. U.S., Japanese and French investigators are still not certain what caused the battery fire aboard an All Nippon Airways 787 in Boston and an overheated, smoking battery on a Japan Airlines 787 in Japan.

The proposed fix includes adding ceramic insulation between the cells of the battery to help keep cells cool and prevent a "thermal runaway" in which one cell overheats and triggers overheating in adjacent cells. It also includes building a stronger, larger stainless steel box with a venting tube to contain a fire and expel fumes outside the aircraft should a battery catch fire again, the sources said. In addition, the plan proposed wiring changes, self-torquing screws that won't come loose and battery alterations to prevent moisture and vibration problems, one of the sources said.

But there was also a plan to use a different battery type or some other longer-term fix, the sources said.

"I have talked to a number of people who are working directly on these batteries. No one is on the Plan-B team," said a person familiar with Boeing's efforts who was not authorized to speak publicly about them.

A second source, who also was not authorized to speak publicly, said Boeing does not view its proposal as a temporary "band-aid" that would be supplanted by another solution later.

Boeing spokesman Marc Birtel said in a statement: "We are encouraged by the progress being made toward resolving the issue and returning the 787 to flight for our customers and their passengers around the world."

Birtel reiterated that hundreds of engineers and technical experts are working "around the clock" to return the 787 fleet to service. "Everyone is working to get to the answer as quickly as possible and good progress is being made," Birtel said.

Boeing's stock closed up 65 cents, or 0.86 percent, at $75.66 on the New York Stock Exchange.

Richard Aboulafia, aerospace analyst with the Teal Group in Virginia, said Boeing needed a backup plan in case the FAA did not approve its proposal.

"It's a bit tone deaf to propose containment and management when the political winds are favoring an elimination of the risk," he said, citing Transportation Secretary Ray LaHood's insistence that the plane would return to flight only when it was "1000 percent safe" and similar remarks by other officials.

"They need to be out there talking about a bigger solution beyond mere containment because the political winds and public opinion are not going to favor a solution that's focused on fire and smoke management," Aboulafia said.

He noted that Airbus had already signaled its plan to switch back to more traditional nickel cadmium batteries for its A350 airliner, but the 787 was far more dependent on electrical power, which would complicate any effort to switch to a different type of battery. A complete redesign could take around nine months to implement, he said.

Others said that kind of solution could take two years.

The U.S. National Transportation Safety Board is still investigating the Boston fire and the Japan Transportation Safety Board is investigating the battery failure in Japan. Neither has found a root cause for the problems.

The sources said the NTSB might never find the root cause because the battery in Boston was severely damaged by the fire.

Given the financial cost of the grounding for Boeing and the airlines that own the jets, estimated at $200 million a month, Boeing decided to address all possible causes with the measures, rather than wait for the NTSB to identify one specific cause, the sources said.

Boeing engineers have been working with outside experts and U.S. government officials to address possible cause of the battery issues. The team includes experts from the U.S. Navy and the National Aeronautics and Space Administration, which uses a lithium-ion battery on board the International Space Station.

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Boeing engineers went through a "fault tree" and "came up with a list of half a dozen things that could have led to problems," said a congressional source who had been briefed on the matter, but was not authorized to speak publicly.

"They have a list of things that it could be, and the fixes are designed to address that list of problems," the source said.

If the NTSB's investigation turns up additional possible causes, those would be added to the mix, another of the sources said.

Asked why the company's extensive testing of the batteries had not revealed problems with the batteries and the electrical systems used to operate them, one of the sources said test environments had limitations and the real test of an aircraft always came when it was actually operating.

If the Boeing plan is approved by FAA Administrator Huerta and Transportation Secretary LaHood, company officials expect the 787 fleet to return to service within eight weeks, one source said.

Another source, who is also familiar with the 787 investigation but not authorized to speak publicly, said a key challenge for Boeing would be to redesign the battery box so that it could truly contain a fire if one occurred.

Despite Boeing's statements about containment being the plan for a battery issue from the start, the blue box that held the current lithium-ion battery was clearly "not designed to contain a fire," said the source.

Another person familiar with the engineering work said the new box would be made of stainless steel nearly half an inch thick. It would be capable of containing an explosion, and would have a tube to vent smoke and flame outside the jet.

However, the source said engineers have raised questions about the safety of venting flames outside the plane, especially if it is on the ground and being fueled. The effect could be something like a flamethrower, this person said.

(Reporting by Andrea Shala-Esa and Alwyn Scott; Editing by Gerald E. McCormick, Dan Grebler, David Gregorio and Gunna Dickson)

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Statement of National Highway Traffic Safety Administration On Possible Fires in Lithium-Ion Vehicles Involved in a Crash

For Immediate Release
Friday, November 11, 2011
Contact: Lynda Tran, 202-366-9550

WASHINGTON, DC — The National Highway Traffic Safety Administration (NHTSA) issued the following statement today regarding the potential risk of post-crash fires in vehicles powered by lithium-ion batteries:

Electric vehicles show great promise as an innovative and fuel-efficient option for American drivers. These vehicles have already demonstrated their potential to save consumers money at the pump and help protect the environment — and they could pave the way to the kind of clean energy jobs that will help our country compete on a global scale. As manufacturers continue to develop vehicles of any kind — electric, gasoline, or diesel — it is critical that they take the necessary steps to ensure the safety of drivers — and first responders — both during and after a crash.

That's why the National Highway Traffic Safety Administration is working with all vehicle manufacturers to ensure they have the appropriate post-crash protocols. Let us be clear: NHTSA does not believe electric vehicles are at a greater risk of fire than other vehicles. It is common sense that the different designs of electric vehicles will require different safety standards and precautions. The Department of Energy and the National Fire Protection Association already collaborate to ensure first responders know the risks and the appropriate steps to take so they can perform their jobs safely given the shock hazard that a damaged electric vehicle may present, and NHTSA will work closely with these organizations to ensure that guidance for the emergency response community reflects the information NHTSA obtains.

In the near term, NHTSA is focused on identifying the best ways to ensure that consumers and emergency responders are aware of any risks they may encounter in electric vehicles in post-crash situations. The agency has asked all of the manufacturers who currently have electric vehicles on the market (or plans to introduce electric vehicles in the near future) to provide information on the protocols they have established for discharging and handling their lithium-ion batteries — including any recommendations for mitigating fire risks in these vehicles. Ultimately we hope the information we gather will lay the groundwork for detailed guidance for first responders and tow truck operators for use in their work responding to incidents involving these vehicles.

NHTSA has carefully investigated an incident involving a fire in a Chevy Volt that occurred more than three weeks after that vehicle had been crash tested as part of the agency's New Car Assessment Program on May 12 of this year. NHTSA has concluded that the crash test damaged the Volt's lithium ion battery and that the damage led to a vehicle fire that took several weeks to develop after the test was completed. That incident — which occurred at the test facility and caused property damage but no injuries — remains the only case of a battery-related fire in a crash or crash test of vehicles powered by lithium-ion batteries, despite a number of other rigorous crash tests of the Chevy Volt separately conducted by both NHTSA and General Motors. In the coming weeks, in collaboration with the Department of Energy, NHTSA will conduct additional testing of the Volt's lithium-ion batteries and will continue to monitor these vehicles — as the agency does with all vehicles on our nation's roadways — should any safety issues arise.

Based on the available data, NHTSA does not believe the Volt or other electric vehicles are at a greater risk of fire than gasoline-powered vehicles. In fact, all vehicles — both electric and gasoline-powered — have some risk of fire in the event of a serious crash. NHTSA urges the following precautions in the event of a crash involving an electric vehicle:

- Consumers are advised to take the same actions they would in a crash involving a gasoline-powered vehicle — exit the vehicle safely or await the assistance of an emergency responder if they are unable to get out on their own, move a safe distance away from the vehicle, and notify the authorities of the crash.
- Emergency responders should check a vehicle for markings or other indications that it is electric-powered. If it is, they should exercise caution, per published guidelines, to avoid any possible electrical shock and should disconnect the battery from the vehicle circuits if possible.
- Emergency responders should also use copious amounts of water if fire is present or suspected and keeping in mind that fire can occur for a considerable period after a crash should proceed accordingly.
- Operators of tow trucks and vehicle storage facilities should ensure the damaged vehicle is kept in an open area instead of a garage or other enclosed building.
- Rather than attempt to discharge a propulsion battery, an emergency responder, tow truck operator, or storage facility should contact experts at the vehicle's manufacturer on that subject.
- Vehicle owners should not store a severely damaged vehicle in a garage or near other vehicles.
- Consumers with questions about their electric vehicles should contact their local dealers.

For more information, visit www.SaferCar.gov.

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Kinki Sharyo selects GS Yuasa to power its ameriTRAM™ Next Generation Light Rail Vehicle

March 15, 2011, Kyoto, Japan: GS Yuasa's LIM30H-8A lithium-ion battery module has been selected by the Kinki Sharyo Co., Ltd. for the company's next generation LRV, the ameriTRAM™. ameriTRAM™ is a 100% low-floor LR designed specifically for the US market.

ameriTRAM™ is able to operate in locations where exter electric power is not always available. Energy stored in th onboard Li-ion batteries is used to power the traction syst and all auxiliary loads in parts of the track where an overh catenary is not available. When external power is availabl is used for all onboard loads and to recharge the batteries needed. The batteries also store regenerative braking ene for reuse. Vehicle testing began in May 2010 at Kinki Sha test track in Osaka, Japan. Demonstrations in the US are under way.

The ameriTRAM™ battery system is based on GS Yuasa's existing LIM30H-8A lithium-ion battery module and was jointly developed by GS Yuasa and Kinki Sharyo. The union of GS Yuasa's proven high performance and high pow lithium-ion batteries and Kinki Sharyo's latest LRV technologies enables operators to meet energy usage goals and provides uncommon value.

GS YUASA manufactures large format lithium-ion cells for aviation, space, electric vehicle (EV) and hybrid electric vehicle (HEV) applications. GS Yuasa also manufactures large format lithium-ion cells, modules and battery management electronics (BME) for industrial automated guided vehicles (AGVs), railway way-side energy storage systems, and industrial hybrid applications such as rail switchers and rubber tire gantry cranes (RTGCs).

The 'LIM30H-8A' module was developed and commercialized specifically for industrial large capacity hybrid system The module's features include:

- **High current charge and discharge capability**
- **Low cell impedance and long service life through minimized of impedance growth rate**
- **Lightweight and compact**
- **Forced air cooling**
- **Battery monitoring electronics and balancing**

Functionality includes: individual cell voltage monitoring, cell balancing, module temperature measurement, state of health, and data communication.

External dimensions	l, w, h: 389, 231, 147 (mm)	**Weight**	19.5Kg
Nominal voltage	28.8V	**Nominal cell voltage**	3.6V
Nominal capacity	30Ah	**Operating voltage range**	23.2~33.2V
Maximum pulse current	600A	**Continuous current**	100A
Operating temperature	0~45 °C	**Monitoring system**	Monitors each cell volta and module temperatur

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For additional information, please contact:

GS Yuasa Lithium Power, Inc

1150 Northmeadow PKWY Suite 118 Roswell, GA 30076 USA 888.GSYUASA (888.479.8272) 678.892.7501 (fax)

media@gsyuasa-lp.com

http://www.gsyuasa-lp.com

saft communiqué de presse press release

N° 18-10

Saft batteries provide high-tech traction battery for Sitras HES hybrid energy storage system on Siemens Mobility’s trams

- *Siemens Sitras HES hybrid energy storage system incorporates a Saft Ni-MH integrated battery system that enables the tram to operate without an overhead contact line (OCL) for distances up to 2,500 metres*
- *First tram with Sitras HES is now in passenger service with MTS in the south of Lisbon, Portugal*

Paris, May 6, 2010 – Saft, the world specialist in the design and manufacture of high-tech industrial batteries, has supplied Ni-MH (nickel-metal hydride) integrated traction battery systems to Siemens Mobility for use in the development of a new generation of trams equipped with the Sitras HES hybrid energy storage system. The first tram with Sitras HES, equipped a Saft battery system onboard, has completed more than one year of successful passenger service trials in Portugal with the Siemens Mobility customer MTS (Metro Transportes do Sul, S.A.), Since the end of 2008, it has been operating services between Almada and Seixal, two cities to the south of Lisbon.

The trams with Sitras HES can operate autonomously, without external power from an overhead contact line (OCL), over long sections of track. The concept is ideally suited for areas where impact on the local landscape must be minimized, such as in historic city centres, and is especially environmentally-friendly as well as saving energy.

The Sitras HES concept comprises two energy-storing components: the Sitras MES mobile energy storage unit based on a double-layer capacitor (DLC) and the traction battery system. The two components work together to provide a very efficient energy storage system.

“Saft’s Ni-MH traction batteries for the Sitras HES system was primarily chosen by Siemens Mobility because they were commercially available and could be integrated in the test programme quickly, without a long development period. Furthermore, they met Siemens stringent specifications in terms of weight, size, reliability and high energy performance”.

Regenerative braking

When the tram is running the energy storage units are charged regeneratively during braking. The vehicle can use this stored energy to travel over distances of up to 2,500 metres over sections of track where no OCL is available. This distance represents a very significant increase in autonomous operation compared with the typical 500 metre capability of a tram relying on battery power only, without regenerative braking. The high energy Ni-MH battery also improves the reliability of the tram service as it allows continued operation when the OCL is temporarily unavailable, such as in the case of failure or planned maintenance.

The Sitras HES system is designed for roof-mounting on the tram and is electrically connected to the vehicle feed-in point by means of a DC/DC-chopper. This new autonomous connection concept, enables, the energy storage system to be integrated into new trams or retro-fitted into existing vehicles. Under optimum operating conditions, the Sitras HES is expected to reduce the future energy demand of a vehicle by up to 30 percent, producing up to 80 tonnes less CO_2 emissions per year.

Sitras HES battery unit

The Sitras HES battery unit has been adapted by Saft from its range of fully integrated battery systems developed to meet the needs of the new generation of tramways. It is based on Saft's NHP Ni-MH cells designed specifically for high power applications to offer excellent power storage in a compact maintenance-free package. To ensure maximum reliability and safety, each battery system incorporates an active cooling device and battery management control (BMC). The unit is supplied to Siemens Mobility as a 'plug and play' package in a custom built tray complete with power and communications connections.

The exact battery system voltage and capacity for future systems would vary according to the specific application. A typical specification would be 44 cell blocks of NHP10-340 cells connected in series, providing a nominal 528 V and capable of storing 18 kWh of energy and sustaining a peak power of 105 kW. The total battery weight is 826 kg.

About Saft

Saft (Euronext: Saft) is a world specialist in the design and manufacture of high-tech batteries for industry. Saft batteries are used in high performance applications, such as industrial infrastructure and processes, transportation, space and defence. Saft is the world's leading manufacturer of nickel batteries for industrial applications and of primary lithium batteries for a wide range of end markets. The group is also the European leader for specialised advanced technologies for the defence and space industries and world leader in lithium-ion satellite batteries. Saft is also delivering its lithium-ion technology to the emerging applications of clean vehicles and renewable energy storage. With approximately 4,000 employees worldwide, Saft is present in 18 countries. Its 15 manufacturing sites and extensive sales network enable the group to serve its customers worldwide. Saft is listed in the SBF 120 index on the Paris Stock Market.

For more information, visit Saft at ***www.saftbatteries.com***

Press contacts

Jill Ledger, Saft Communications Director, Tel: + 33 1 49 93 17 77
e-mail: jill.ledger@saftbatteries.com

Marie-Christine Guihéneuf, Saft IBG Communication Manager, Tel: + 33 1 49 93 17 16
e-mail: marie-christine.guiheneuf@saftbatteries.com

Andrew Bartlett, Six Degrees, Tel: + 44 (0) 1628 480280
e-mail: andrew.bartlett@sixdegreespr.com

STADLER
Clevere Lösungen auf der Schiene

MVG

Tram without overhead line - Battery-powered tram for Munich produced by Stadler Pankow GmbH sets a new world record

Velten, 25.05.2011 – A Munich tram, type Variobahn, is on its way into the Guinness Book of Records. Today, the vehicle which is equipped with a newly developed lithium ion battery drove 16 km without overhead lines and with this result, the tram set a new record for the book of world records. Thus, the attempt which was performed on a test track in Velten, took place under the supervision of a notary and the accompaniment by experts. The pantograph of the Variobahn had to be sealed for the duration of the world record attempt. The tram which was staffed with two drivers was only allowed to have a standstill of 5 seconds maximum for the change of the driving direction on the single-track that has a length of approx. 3.5 km. All activities were additionally supervised by track officials next to the track and documented with cameras. In order to be published in the Guinness Book of Records, the Variobahn had to drive at least 1 km only battery-powered.

The tram, which is intended to drive in Munich, is a Variobahn produced by Stadler Pankow GmbH. The Munich city utilities (Stadtwerke München SWM) have decided that the vehicle for the Munich transport corporation (Münchner Verkehrsgesellschaft MVG) is equipped with the high-performance battery to be able to realise an operation without overhead lines on a section in the Bavarian capital. A specific application would be the so-called ring road north. It is proven to have an especially high traffic benefit, because it would be possible to establish a tangential connection with a length of approx. 8 km between Neuhausen-Nymphenburg to Bogenhausen with a gap closure of only approx. 2 km. According to all forecasts, this connection will be highly frequented and thus contribute effectively to easing the burden of the inner-city roads. A further connection to St. Emmeram would allow an extension of up to 13 km. A section of one kilometre of the new line crosses the English Garden.

For this very reason, a first plan approval procedure failed in 2001. At that time, the responsible approving authority was apprehensive of the fact that the overhead line and the masts had a negative effect on the landscape. Hence, SWM/MVG now plan to drive through the English Garden with a battery-powered tram, without the need of overhead lines.

The battery, that has a weight of 380 kg, meets all requirements emerging from the Munich track characteristic. Among other aspects, the length of the track without overhead line through the English Garden (approx. 1 km), one passenger stop, another stop required due to operational reasons, each time with braking and start driving as well as the topography were taken into consideration. Furthermore, the battery is designed for passing this section with the tram not only one time but two times without the need of recharge, given that, apart from that, it is driven by using the overhead line and the recharging of the storage is enabled. As soon as the technical supervisory authority granted the approval for the vehicles type Variobahn to the government of Upper Bavaria, the test vehicle will return to Munich. Further test drives will be performed in the network of the MVG in Munich. If it turns out during these test drives that the battery technology works smoothly and meets all requirements, SWM/MVG strive for another application for plan approval procedure for the ring road north.

The battery tram is one of four vehicles of the first delivery lot for Munich. Ten further Variobahn vehicles are currently being assembled and they will be delivered to SWM/MVG until the end of the year 2011. All vehicles are prepared for the retrofitting with batteries.

Michael Daum, chairman of the board of Stadler Pankow GmbH:”After successfully being in worldwide operation and thereby having driven more than 30 million kilometres, thanks to modern technology, the Variobahn is now in a position to drive considerable distances without overhead lines. Stadler makes tram history with this test drive today.”

Herbert König, chairman of the board of MVG and CEO of SWM traffic: “Since several years we have been dealing with the possible application of energy storages on a tram vehicle. Thereby, the different possibilities have been discussed intensively with the industry. First experiences were also taken into consideration, e.g. the battery application on the light rail vehicle in Nice. A lithium ion battery is best suitable for our first application – crossing a section with a length of 1 km. This type of battery stores the energy slower than supercaps, which are used in Heidelberg for example. However, they can absorb more energy and are thus capable of crossing longer distances without the need to recharge. Today’s attempt showed that, thanks to the lithium ion battery, we can easily realise an operation without overhead line in the English Garden

Further on, König said: “One thing is certain: In contrast to today’s record attempt during which the distance was demonstrated that is technically possible today, it is important for practical applications that the battery is designed exactly adjusted to the local requirements, precisely fitted – also with regards to the possible axle load of the vehicles – and as economically as possible. An important aspect is that the battery discharge is normally only 10-15%, because in this case, the battery has the highest durability. The battery is exactly designed and optimized for the application case ‘ring road north Munich’: discharge of the battery when crossing the English Garden only to 85-90 % of its capacity, afterwards recharge under the overhead line of the rest of the route. Like this, a stable operation with sufficient reserves and optimized battery durability would be possible. This was proven today! “

Editor and contact information:

Stadler Pankow GmbH
Katrin Block
Lessingstrasse 102
13158 Berlin
phone +49 30 9191-1501
mail Katrin.Block@stadlerrail.de

Stadtwerke München (SWM)
Münchner Verkehrsgesellschaft (MVG)
Public relations department
80287 Munich
phone + 49 89 2361-5042
mail presse@swm.de

Development of Contact-Wire/Battery Hybrid LRV

Masamichi OGASA
Senior Researcher, Laboratory Head, Traction Control, Vehicle Control Technology Division

Contact-wire/battery hybrid vehicles run on a hybrid power source that enables energy to be fed from contact wires and/or onboard batteries. Regenerated energy is returned to the contact wires and/or onboard batteries during braking in track sections, thereby ensuring the effective utilization of energy (Fig. 1). In track sections where no contact wires are installed, such vehicles can run using energy supplied only from the onboard batteries (Fig. 2).

In electrified track sections, hybrid running saves energy because regeneration cancellation does not occur, thereby improving the reliability of the regenerating brake. Additionally, running in non-electrified track sections (which offer savings in terms of contact wire installation and maintenance costs) prevents the degradation of urban landscapes to preserve the value of sightseeing resources and improves passenger convenience by enabling through-operation to/from electrified track sections.

As one of the targets of this study, the Traction Control Laboratory developed a contact-wire hybrid car and had it manufactured. The data of running distance after one spell of charging using only energy from the onboard batteries, and energy consumption during hybrid running in actual track sections compared with that of existing inverter vehicles was acquired. And the battery performance in low-temperature areas was also checked.

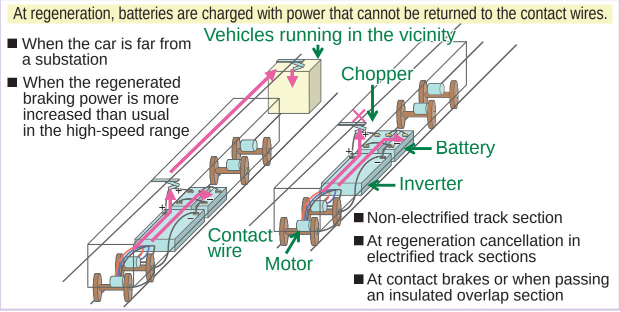
As another target, the laboratory developed a method of charging to quickly supply energy to the vehicles in midway stations distributed at intervals of several kilometers, while aiming at continuous running in non-electrified track sections using only energy from the onboard batteries.

The purposes and results of the study are outlined below.

(1) The Traction Control Laboratory developed the various element technologies required to enable continuous battery driving. It adopted, for example, a system for contact charging through a pantograph from rigid contact wires, and conducted a stationary test at a charging current of 1,000 A to confirm that the contact point would not melt. It also developed a structure to cool the onboard lithium ion batteries (thereby suppressing increases in their temperature), determined the interval between the cells in the battery module, and ascertained the required volume of cooling air through tests and thermal simulation. The laboratory then installed a cooling fan with a maximum capacity of 5 m/sec on the vehcile. It also developed a dual-voltage contact-wire hybrid exchanger with a quick-charge function and a capacity of 600 kW, suitable for application both to 1,500 V and 600 V DC voltages.

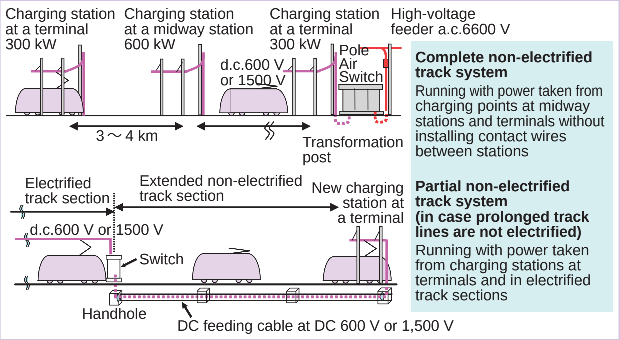
At regeneration, batteries are charged with power that cannot be returned to the contact wires.

- When the car is far from a substation
- When the regenerated braking power is more increased than usual in the high-speed range



- Non-electrified track section
- At regeneration cancellation in electrified track sections
- At contact brakes or when passing an insulated overlap section

Fig. 1 Contact-wire/hybrid power flow (at regeneration)


Charging station at a terminal 300 kW
Charging station at a midway station 600 kW
Charging station at a terminal 300 kW
High-voltage feeder a.c.6600 V
d.c.600 V or 1500 V
Pole
Air Switch
3～4 km
Transformation post
Electrified track section
Extended non-electrified track section
New charging station at a terminal
d.c.600 V or 1500 V
Switch
Handhole
DC feeding cable at DC 600 V or 1,500 V

Complete non-electrified track system
Running with power taken from charging points at midway stations and terminals without installing contact wires between stations

Partial non-electrified track system (in case prolonged track lines are not electrified)
Running with power taken from charging stations at terminals and in electrified track sections

Fig. 2 Running in non-electrified track sections

(2) The Laboratory had a contact-wire/battery-type hybrid car manufactured that reflected the element technologies developed, including those introduced above, in its design (Fig. 3).

In consideration of the number of batteries to be mounted for running in non-electrified track sections, the car was designed with an onboard battery system featuring a nominal capacity of 72 kWh at a nominal voltage of 600 V. It was demonstrated that batteries and a charger could be mounted in a compact formation on the LRV carbody with the smallest dimensions of all LRV cars in Japan.

(3) The laboratory implemented a test on quick charging from rigid contact wires for the LRV car developed (Fig. 4). In this test, the onboard batteries were charged over a period of about 60 seconds at a charging current of 1,000 A with enough energy to run 4 km or more (Table 1). The test therefore proved the feasibility of quick charging with no melting at the contact point and restriction of the temperature increase in the onboard batteries to 3° C.

(4) The LRV car developed was put into test on a commercial service line of Sapporo City's Transport Bureau. It ran 25.8 km on an actual operation diagram while heating the passenger room without power from external sources, and recorded a regeneration ratio of 41% (the volume of regenerated power divided by the power consumed in running) (Fig. 5). During running in electrified track sections while charging the batteries, energy consumption was cut by 30% over that of existing inverter cars.

This study was promoted under a contract with the NEDO (New Energy and Industrial Technology Development Organization).

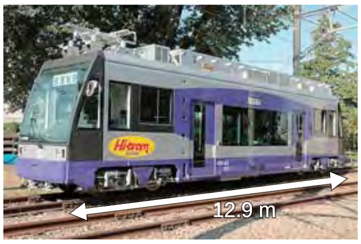


Fig. 3 Contact-wire/battery hybrid LRV

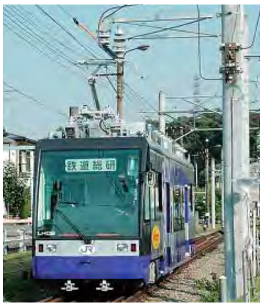


Fig. 4 Quick charging from rigid contact wires

Table 1 Energy obtained by quick charging

Battery charging current and duration	Power charged at battery terminals	Running distance after a one short time of quick charging (without air conditioning)	Running distance after a one short time of quick charging (at the maximum air conditioning load)
1,000 A x 61 sec	13.7% of the capacity	Equivalent to 7.9 km	4.0 km or over
500 A x 3 min and 16 sec	21.9% of the capacity	Equivalent to 12.7 km	6.4 km or over

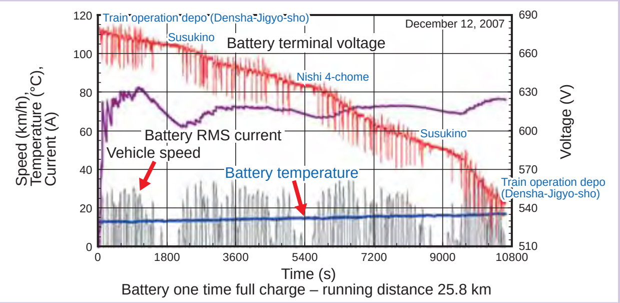
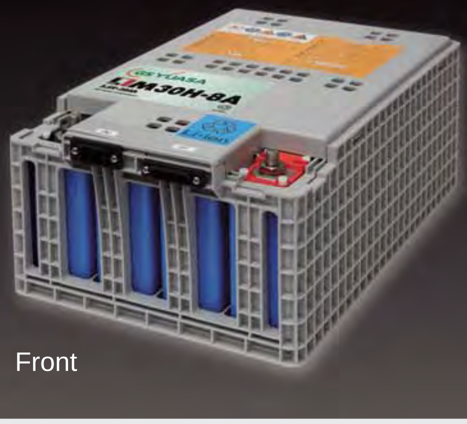


Fig. 5 Running with batteries after a spell of charging

Lithium ion battery for Industrial use
LIM series


Front

Back

Overview

The LIM series, lithium-ion rechargeable battery for industrial applications, has been developed based on our state of the art technology and extensive experience in manufacturing small lithium-ion and large-scale industrial batteries. As a high energy and power source, the LIM series is your answer for long life in a compact size for most industrial applications.

Applications

- Hybrid crane systems
- Hybrid train
- Hybrid vehicle
- AGV(Automated Guided Vehicle)
- Power storage system for railway
- Load leveling systems
- Other industrial systems

Features and Benefits

- High charge / discharge power density
- Sealed structure
- No memory effect
- Easy periodical check
- Outstanding cycle life
- Fan-forced air cooling control with thermal sensor
- Integrated module design

Specifications

Model	Cell Qty	Charge Voltage (V)	Dimensions(mm)			Mass (Kg)	Maximum Charge Current(A)	Maximum Disharge Current(A)
			Length	Width	Height			
LIM30H-8A	8	28.8	414	231	147	19.5	600 (20C)	600 (20C)

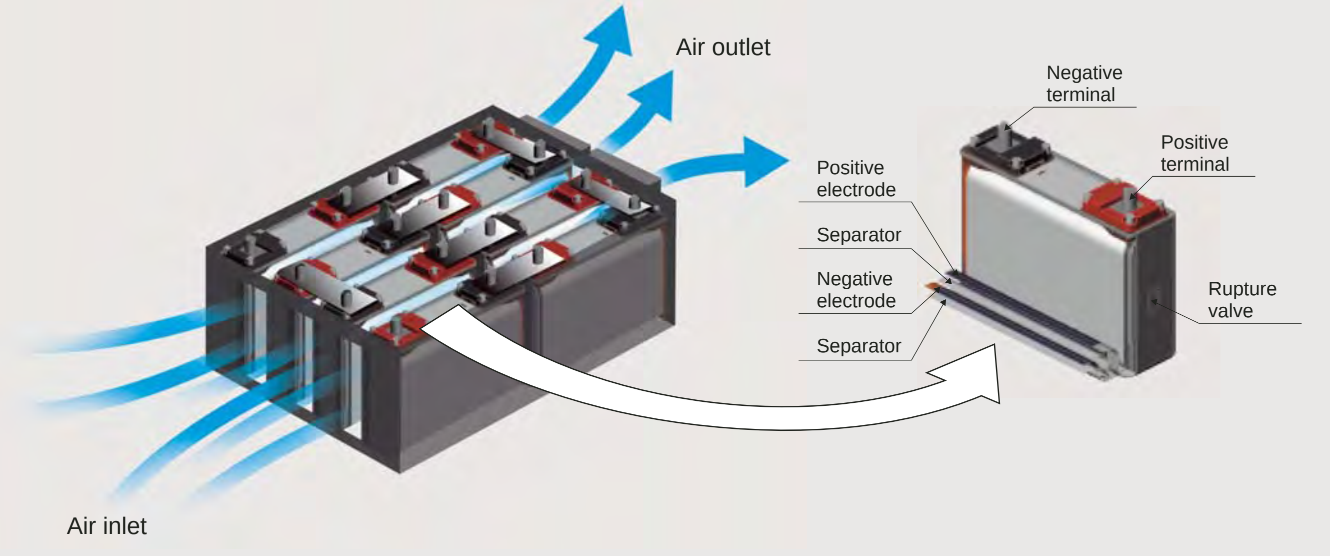
Charge temperature (˚C) : 0〜45 Discharge temperature (˚C) : 0〜45

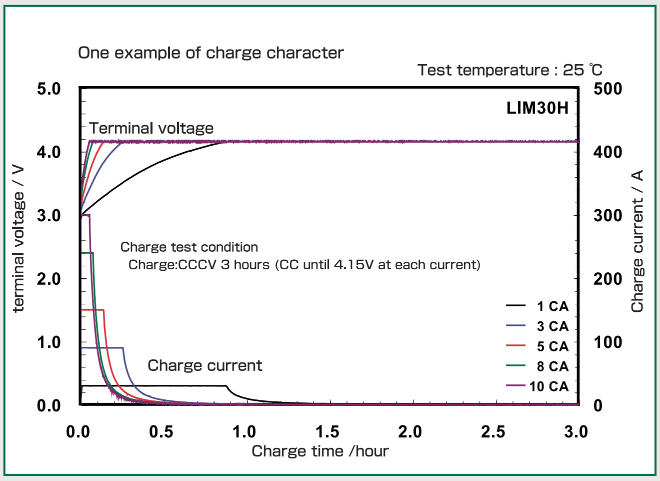
Monitoring system

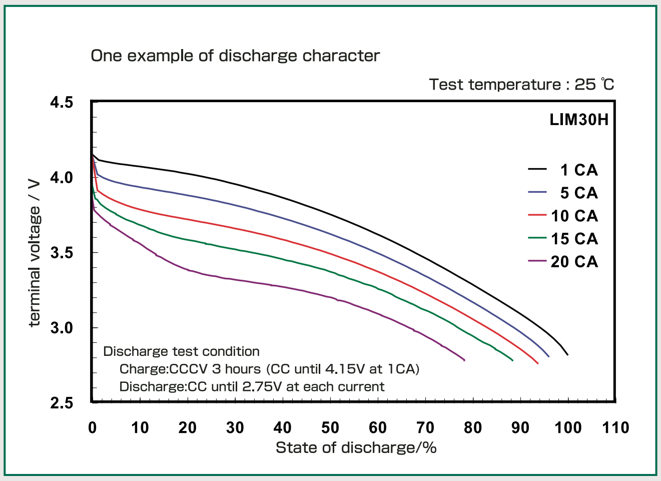
Items	Functions	Items	Functions
Voltage monitoring	Each cell voltage is monitored.	Alarm signals	Overvoltage,Undervoltage,
Temperature monitoring	Each module temperature is monitored.		High temperature,Low temperature
Status signals	Voltage rise,Voltage fall,Fan operation	Balancer	Voltage difference between each cell is controlled.

Structure of Battery Module

Structure of a single cell







Safety and protection of Lithium Ion battery

GS Yuasa LIM modules are equipped with protective functions that can detect overcharge, overdischarge, high temperature and other abnormal operating conditions. The LIM modules must be operated with a dedicated charger that can monitor the LIM battery management signals and automatically terminate charging or discharging.

Contacts

Asia, Europe and others:

GS Yuasa Power Supply Ltd.
(Shiba-koen Tower)2-11-1,Shiba-koen,Minato-ku,
Tokyo 105-0011, Japan
TEL: +81-3-5402-5816 FAX: +81-3-5402-5832..
http://www.gs-yuasa.com/us

America:

GS Yuasa Lithium Power,Inc
1000 Mansell Exchange West, Suite 350
Alpharetta, GA 30022
Toll Free:888.GS Yuasa/888.479-8272 FAX:678-739-2132
http://www.gsyuasa-lp.com

News Release

March 26, 2012

GS Yuasa Corporation

JR Freight's First Mass-produced Hybrid Locomotive Commences Service with GS Yuasa's Industrial-use Lithium-ion Battery Module Installed

GS Yuasa Corporation (Tokyo Stock Exchange: 6674) announced today that its industrial-use lithium-ion battery module has been installed in Japan Freight Railway Company's ("JR Freight") first mass-produced hybrid shunting locomotive, which was launched from the Tokyo Freight Terminal Station in February 2012.

Prior to mass production, JR Freight tested GS Yuasa's lithium-ion battery modules in a prototype locomotive (model HD300-901) from April 2010 under various operating conditions to verify its environmental performance and other capabilities. The performance of the GS Yuasa lithium-ion battery modules was highly rated, and as a result JR Freight decided to install the modules in its first mass-produced locomotive (HD300-1).

The power for the hybrid shunting locomotive is provided through a system that combines a small diesel engine generator with high-capacity lithium-ion batteries. These batteries provide a crucial support function as they store regenerative braking energy and use the energy to power the diesel engine during start-up acceleration and at other times. Compared to conventional diesel locomotives (DE-10), this system reduces nitrogen oxide (NOx) emissions by 61%, fuel consumption by 36%, and noise levels by 22db.

Currently, many of Japan's railway operators are conducting field tests on new hybrid railway vehicles which equip railway vehicles with storage batteries. GS Yuasa is providing lithium-ion batteries for these railway vehicles and expects wider adoption of the batteries in the future as mass-produced railway vehicles commence service. GS Yuasa will strive to expand the adoption of industrial-use lithium-ion battery modules in environmentally friendly railway vehicles in order to further contribute to lowering the environmental burden.

Features of the LIM30H-8A Lithium-ion Battery Module

1. High current charge/discharge performance

   The maximum current capacity is 600A and the Direct current capacity is 100A, which ensures stable charge and discharge performance.

2. High input-output performance and longer operating life through reduced internal resistance

3. Lightweight, compact design

   The use of plastic resins in the outer module casing enables a lightweight, compact design. The plastic resins have superior insulation properties, enabling them to be used even under high voltage conditions.

4. Forced-air cooling

   The modules use cooled air, which helps to raise the efficiency of the cooling system.

5. Standard battery-monitoring system to continuously monitor battery status

   A proven battery-monitoring device for industrial-use lithium-ion batteries is a standard feature. The device continuously monitors the voltage of all cells as well as the module temperature. The device has a function to send battery data to the charging device and the system.

   By adding a GS Yuasa battery management unit (BMU), battery data can also be output to external devices.

LIM30H-8A Lithium-ion Battery Module Specifications

Dimensions (mm)	W:231 x D:389 x H:147	Mass (kg)	approx. 20
Nominal voltage (V)	28.8	Nominal voltage per cell (V)	3.6
Capacity (Ah)	30	Operating voltage range (V)	23.2 ~ 33.2
Maximum current (A)	600	Direct current (A)	100
Temperature range (˚C)	0 ~ 45	Monitoring device	All-cell monitoring; Module temperature monitoring

Images

1. LIM30H-8A Lithium-ion Battery Module

2. JR Freight's first mass-produced hybrid shunting locomotive (HD300-1)

Access the below link for a clip of the HD300-1 in action
http://www.gs-yuasa.com/jp/news/movie/20120326.wmv

Overview of lithium-ion batteries installed in hybrid shunting locomotive

Configuration	LIM30H-8A x 78 units (26 units connected in series/ 3 units connected in parallel)
Nominal voltage (V)	748.8
Capacity (Ah)	90
Total energy output (kWh)	67.4

For additional information, please contact:

GS Yuasa Lithium Power, Inc
1150 Northmeadow PKWY Suite 118
Roswell, GA 30076
USA 888.GSYUASA (888.479.8272) 678.892.7501
(fax) media@gsyuasa-lp.com
http://www.gsyuasa-lp.com

Development of New Generation Supercapacitors for Transportation Applications

Alexis Laforgue[*], Dongfang Yang[‡], Lei Zhang[†], Yves Grincourt[‡],

Jiujun Zhang[†] and Lucie Robitaille[*]

[*] Industrial Materials Institute (IMI), Boucherville, QC
[†] Institute for Fuel Cell Innovation (IFCI), Vancouver, BC
[‡] Center for Automotive Materials and Manufacturing (CAMM), London, ON

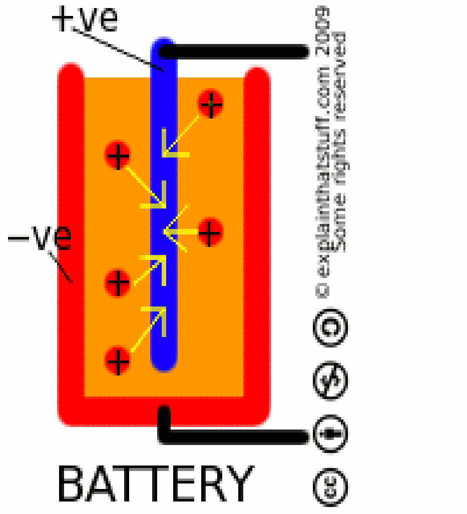
National Research Council Canada Conseil national de recherches Canada

Canada

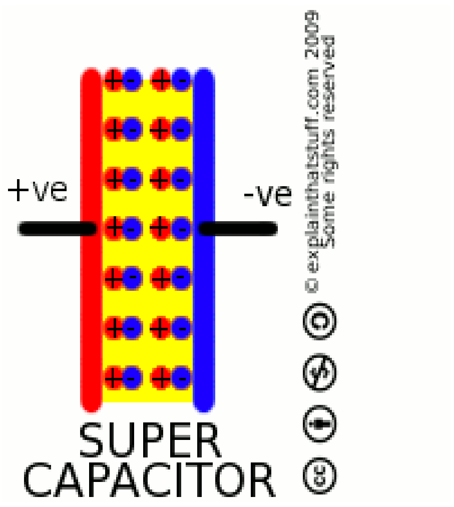
Outline

- Description of electric energy storage devices
- Description of supercapacitors
- Objectives of the project
- Results
    - Active materials
    - Current collectors
    - Separators
    - Complete cell testing
- Conclusions

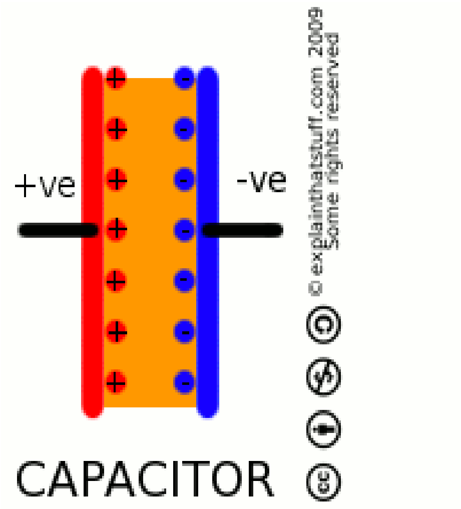
Electric Energy Storage Devices



stores energy using **chemical reactions** happening between an electrolyte, a positive electrode and a negative electrode.



stores more energy than ordinary capacitors by creating a **double layer of separated charges** between two plates made from porous, typically carbon-based materials .



consists of two conducting surfaces separated by an insulating material (dielectric).

Stores energy in an **electric field.**

Electric Energy Storage Devices

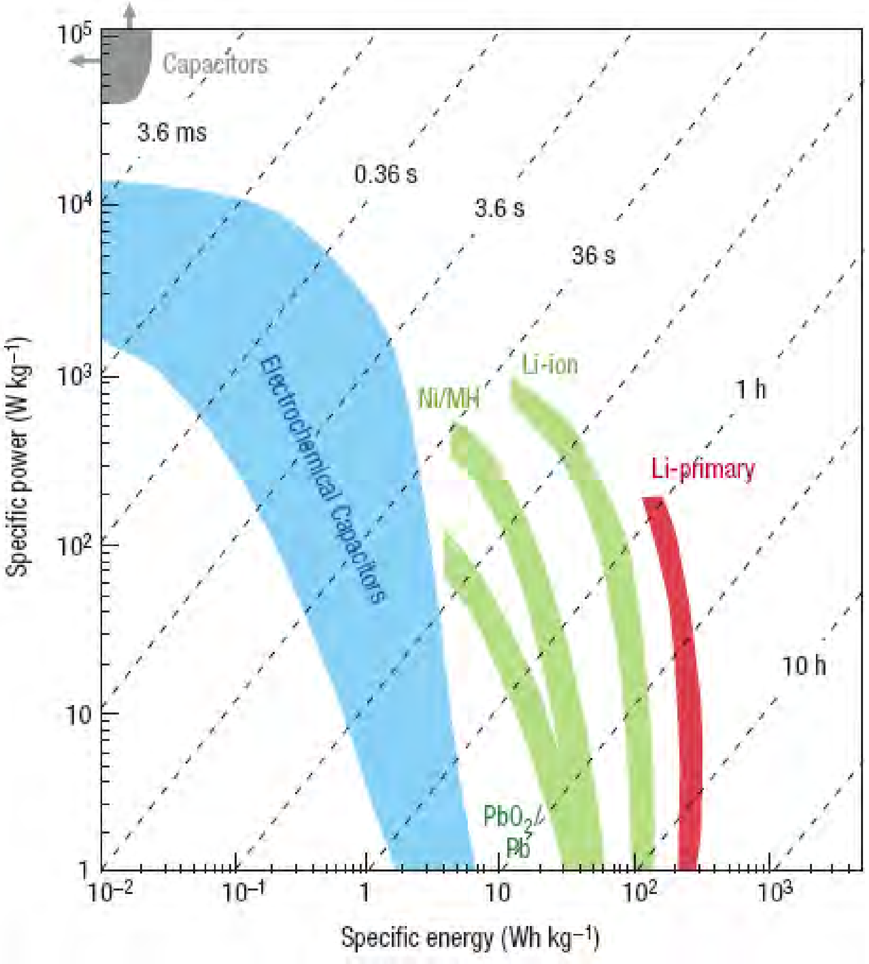
DEVICE	BATTERY	SUPERCAP	CAPACITOR
CHARGING TIME	hours	msec - minutes	µsec - msec
DISCHARGING TIME	minutes - months	msec - minutes	µsec - msec
CYCLE LIFE	200 - 1000	10^6 -10^8	10^6 -10^8
SPECIFIC POWER (W/Kg)	< 500	1000 - 3000	> 10,000
SPECIFIC ENERGY (Wh/Kg)	50 - 300	0.5 - 5	< 0.01

Supercapacitors and batteries are complimentary technologies!

Supercapacitors

Ideal devices for delivering a quick surge of power

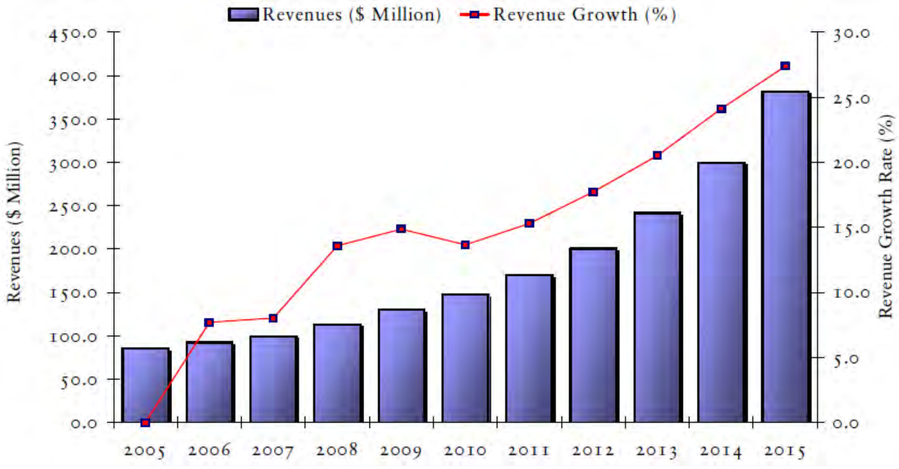
- ➡ Stop-start applications
- ➡ Regenerative braking
- ➡ Power vehicle accelerations
- ➡ Provide power during stops (radio, lights, air conditioning) , while battery provides range
- ➡ Cold starts



P. Simon & Y. Gogotsi, *Nature Materials, Vol.*7 (2008) 845-854.

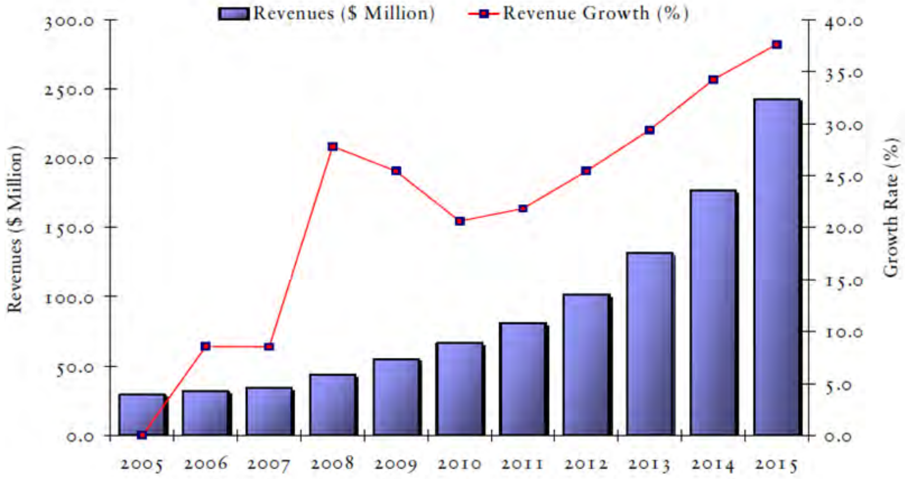
Supercapacitors Market Forecast

Global Market Growth Forecast



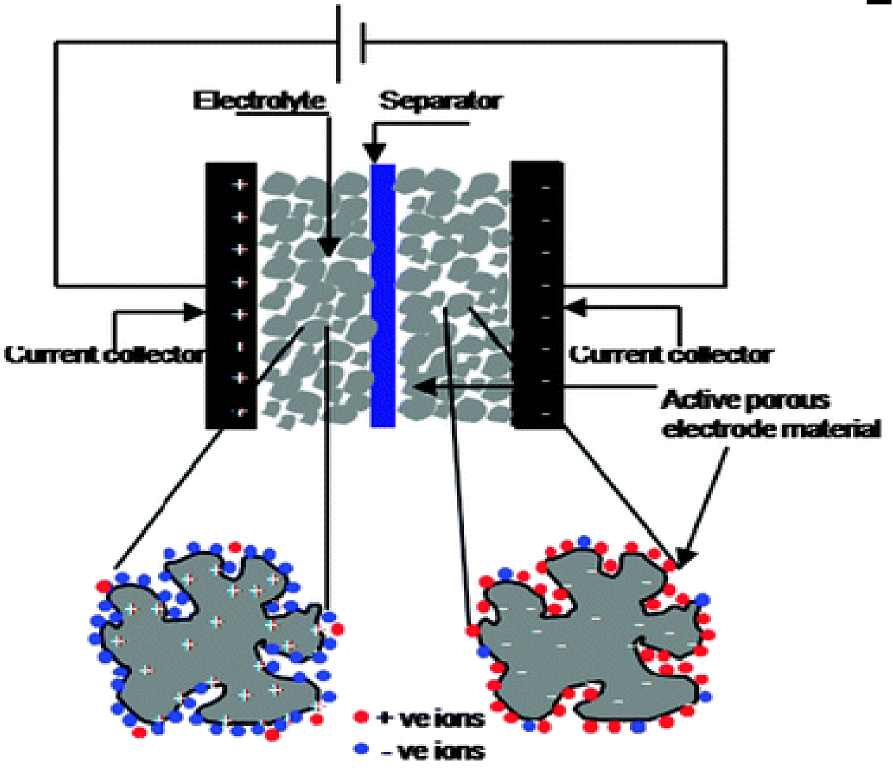
Maxwell's Boostcap®

Transportation Market Forecast



Data from *World Ultracapacitor Markets - Frost &Sullivan report, 2009*

Supercapacitors: Challenges



Graphic from: Zhang et al., *Chem. Soc. Rev., 38* (2009) 2520-2531.

1) Improve performance

- *Increase the energy output*
  - high surface area nano-carbons
  - high capacitance metal oxides or conducting polymers
- *Increase the power output*
  - increase electronic conductivity of active materials
  - texturing current collectors (decrease charge transfer resistance)
  - highly porous separators (increase ion mobility)
- *Increase voltage that device can handle*
  - metal oxides in aqueous medium (2V)
  - ionic liquid electrolytes (4V)

2) Decrease costs

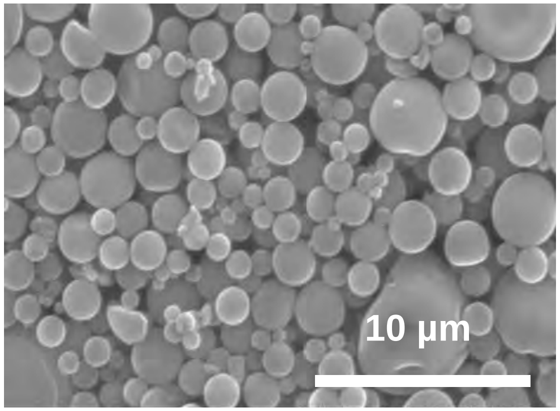
Project Objectives

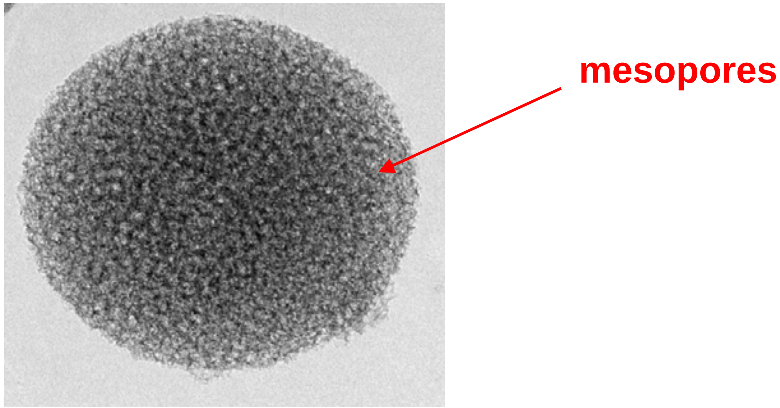
- Increase both the energy density and the power density of supercapacitors, using **low cost** components and an **asymmetric configuration** (MnO_2/carbon).
- Investigate the following key issues :
  - **Active materials**: "core" component of the device
  - **Electrolyte**: for better ion intercalation into the active materials
  - **Current collectors**: for a better interface with the active materials
  - **Separator**: for a better ion freedom of movement in the electrolyte
- Evaluate lab scale supercapacitor cells to meet the requirements of transportation applications.
- Develop scale-up strategies for the production of full-scale prototypes.

Active Materials

Development of high surface area mesoporous carbons

Controllable synthesis of porous carbon spheres by template-assisted ***ultrasonic spray pyrolysis*** (USP, **patented by IFCI**).





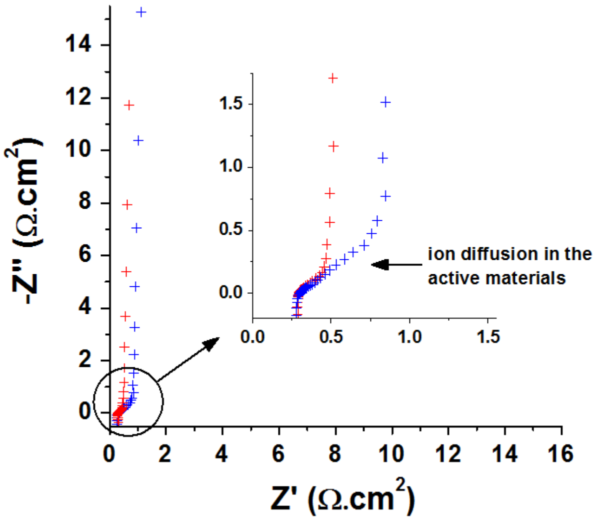
Characteristics of MPC:

- Particle size: 1-5 µm
- Pore size: ~ 7 nm
- Specific surface area : ~ 1800 m^2/g

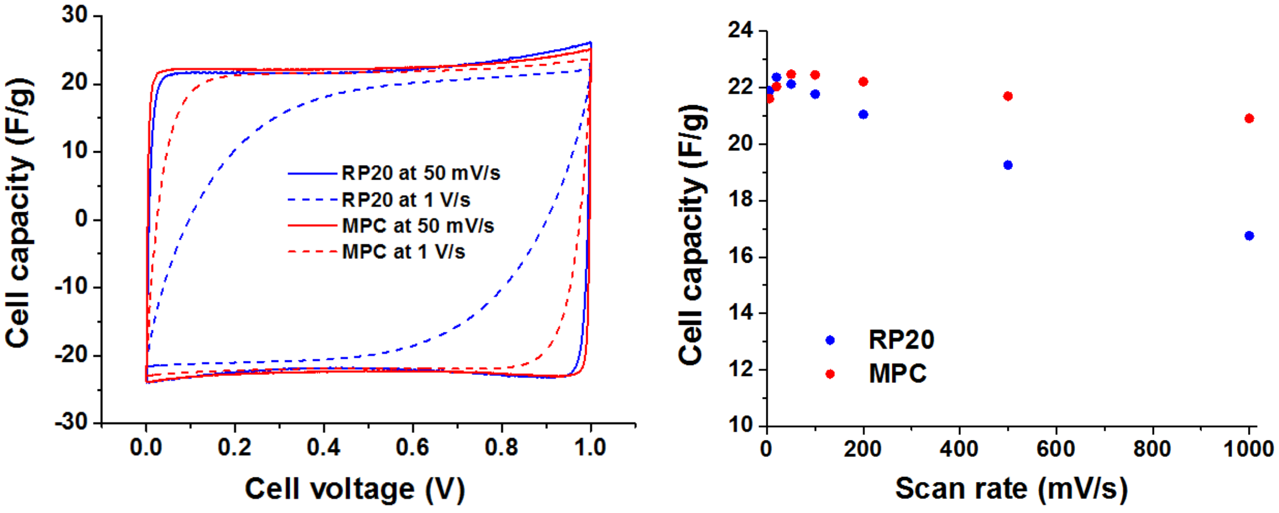
Active Materials

Electrochem. testing of MPC in aqueous supercapacitors

Impedance spectroscopy



Cyclic voltammetry



- Lower diffusion resistance to ions in the porosity of MPC compared to a typical activated carbon (RP20)
- Similar capacity (cell ~ 22 F/g, electrode ~ 90 F/g)
- Better ion mobility in the MPC (probably due to a more open structure)
- Higher capacity retention at high scan rates (high power demand)

Active Materials

MnO_2 as positive active material in supercapacitors

- **Highly capacitive:**
  - theory: ~ 1200 F/g
  - actual: from 100 F/g (bulk phase) to 700 F/g (composites with conducting nanocarbons)
- **Low electric conductivity** (high resistance)
- Many different crystalline structures
- **Important overpotential of water oxidation** (cell voltage increased over 1.23 V)

Chemical synthesis

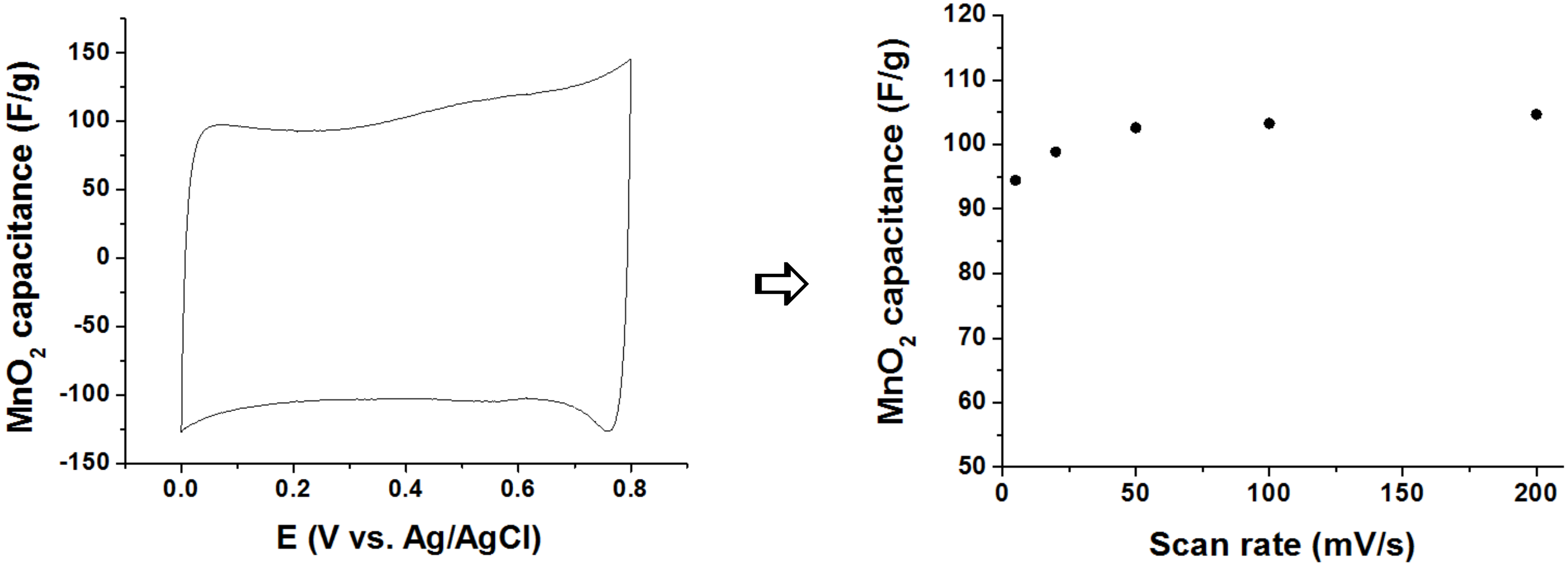
- Very simple chemistry
- Multi-gram scale
- Birnessite type obtained (lamellar structure)

$$MnO_4^- + Mn^{2+} \xrightarrow[\text{base}]{\text{strong}} 2\ MnO_2$$

Active Materials

Electrochem. testing of MnO_2 in aqueous supercapacitors

Cyclic voltammetry

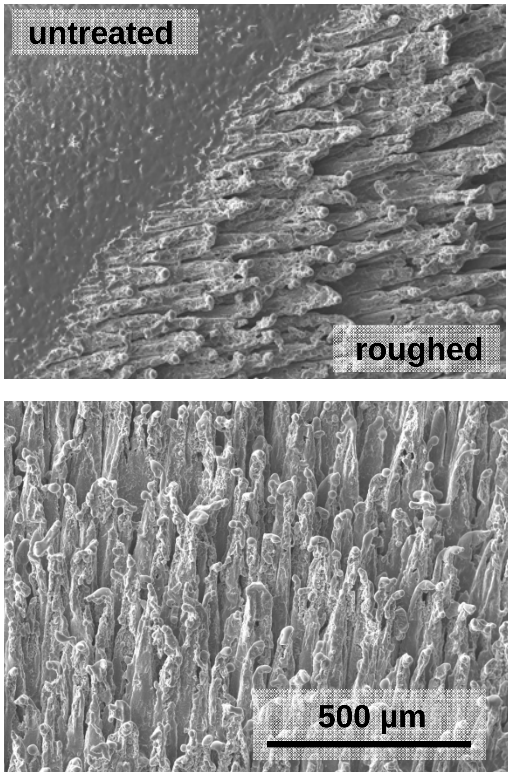


- Typical rectangular charge/discharge profile
- Capacitance: ~ 103 F/g (corresponding to bulk MnO_2)
- High capacitance retention at high scan rate

Current Collectors

Surface roughening of stainless steel and aluminum

- Increase the interface with the active materials
- Improve the mechanical anchoring of the active materials



SEM pictures of roughened Al foil

EDS surface elemental mapping

Element	Weight%	Atomic%
Carbon	3.78	8.11
Oxygen	1.03	1.67
Aluminum	94.01	89.76
Iron	0.81	0.37
Silver	0.37	0.09
Total	100.00	

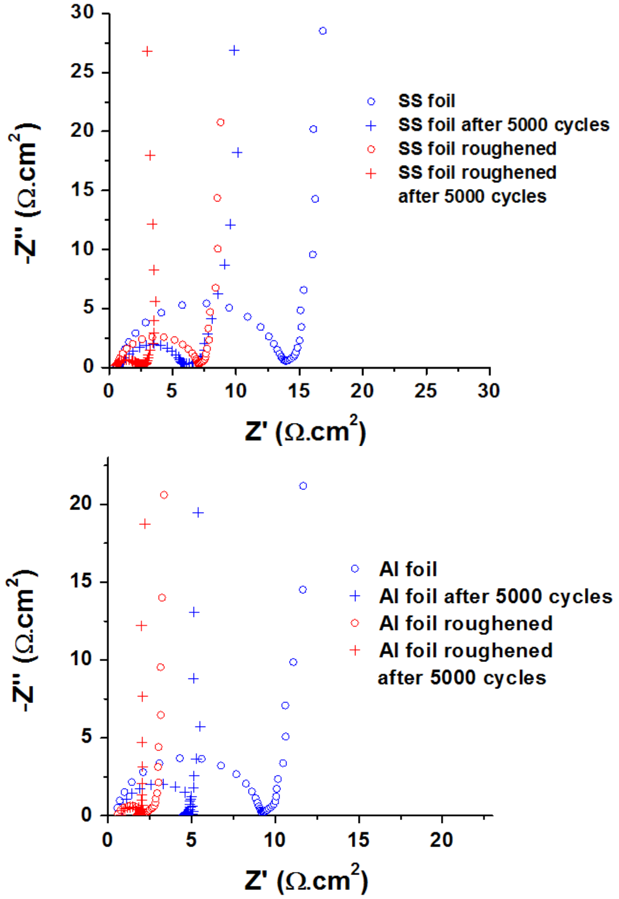
Low oxidation level ensuring
low interface resistance

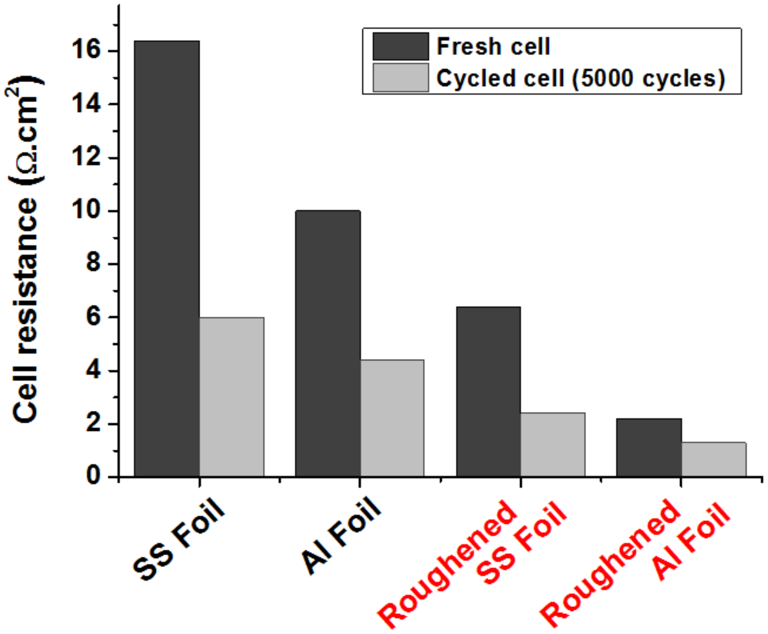
Current Collectors

Electrochemical testing in supercapacitor cells

(conventional symmetric carbon-based cell in mild aqueous electrolyte)

Impedance of SS and Al current collectors



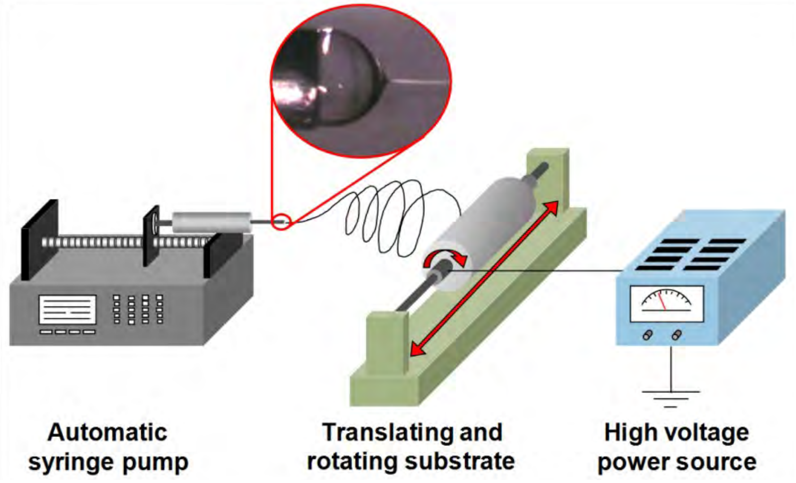


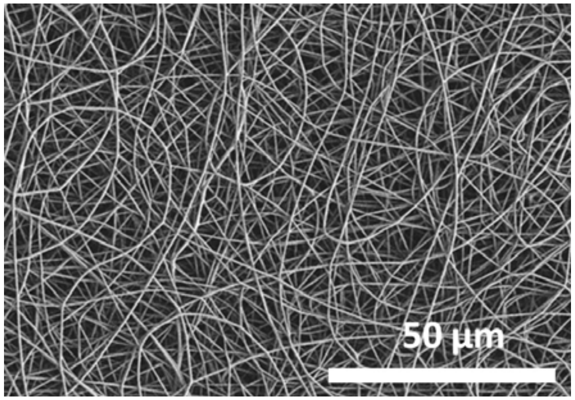
- Higher interface area with the active layer
- Better adhesion of the active materials

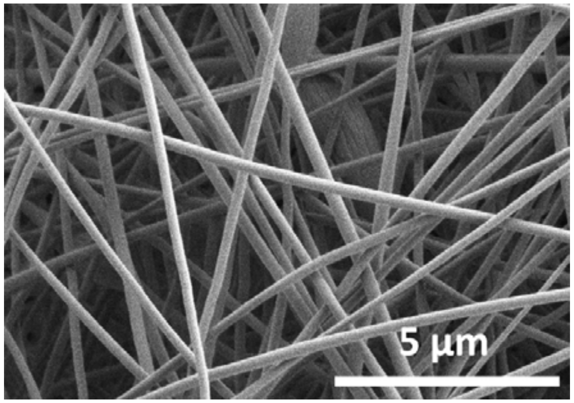
⇨ **Lower cell resistance**

Separators

Electrospinning of nanofibrous nonwoven separators







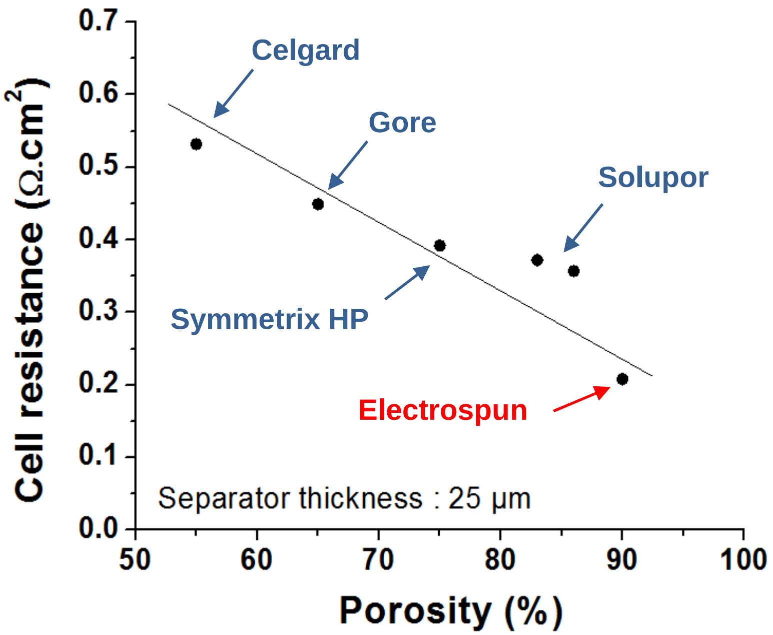
Electrospun separator characteristics:

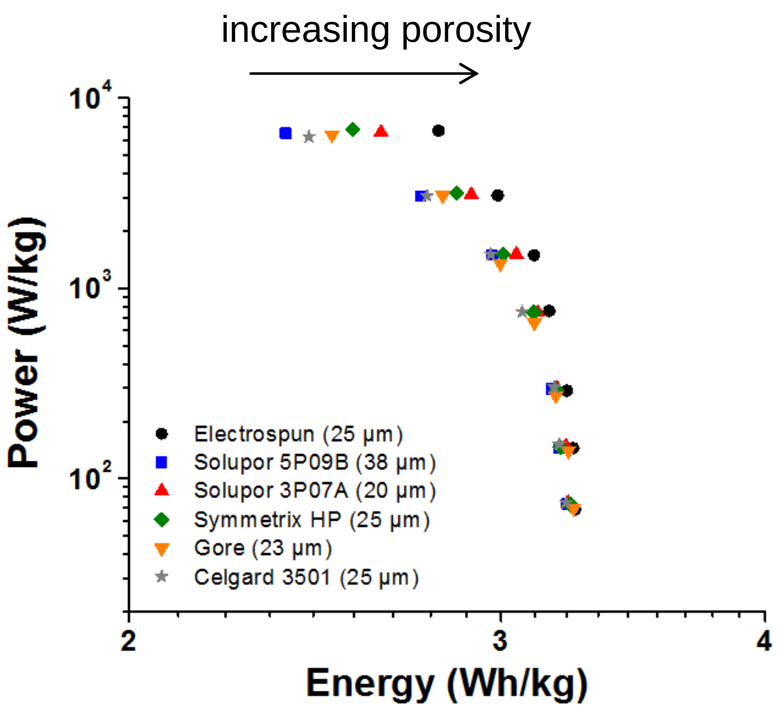
- Material: polyacrylonitrile
- Fiber diameter: 240 ± 30 nm
- Membrane thickness: 25 ± 3 µm
- Membrane porosity: 90 %

Separators

Comparative testing with commercial separators

(conventional symmetric carbon based cell in mild aqueous electrolyte)





- Higher porosity and pore size
- Better ion motion
- Lower internal cell resistance

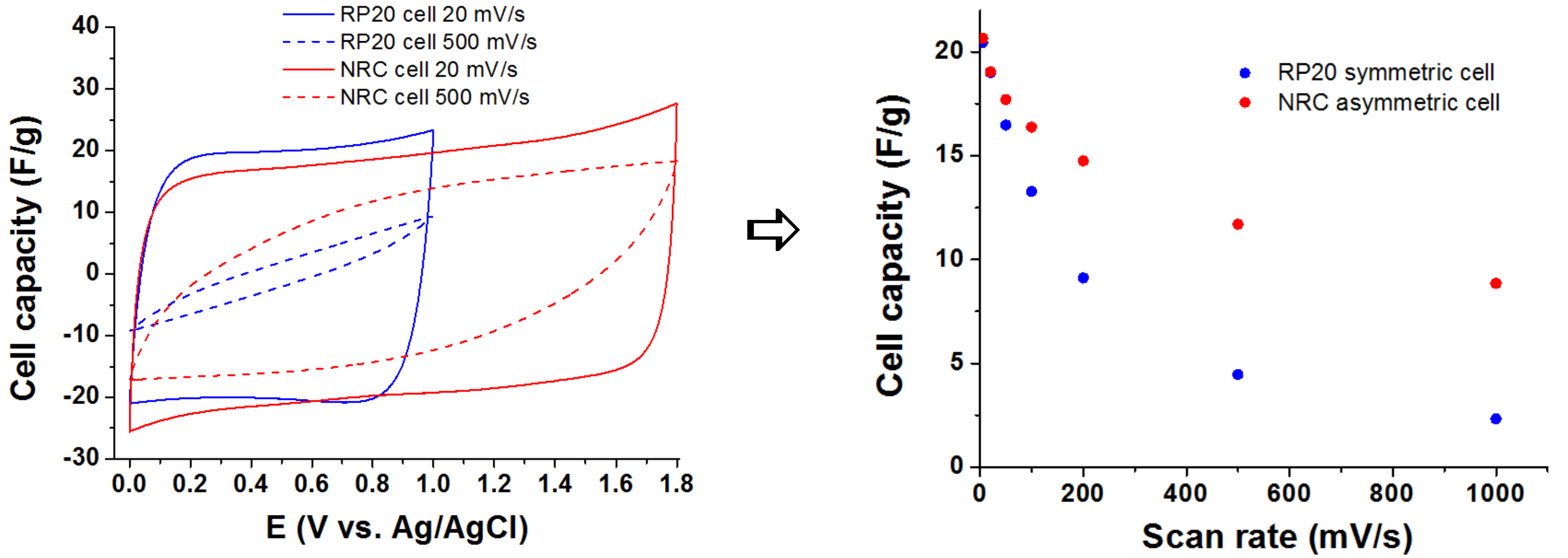
⇨ **Improved power and energy output**

NRC Asymmetric Cell Design

	State-of-the-art cell	NRC cell design
Cell configuration	Symmetric (carbon/carbon)	**Asymmetric** (MnO_2/carbon)
Current collectors	SS foil (AISI 316L)	**Surface roughened** SS foil (AISI 316L)
Separator	Gore (hydrophilic PTFE, 23 µm)	**Electrospun** (polyacrylonitrile, 20 µm)
Electrolyte	Na_2SO_4 0.5 M in water	Na_2SO_4 0.5 M in water
Active layer	Activated carbon (Kuraray, RP20)	**MnO_2** as positive material **MPC** as negative material
	Ketjenblack as conducting additive	Ketjenblack as conducting additive
	PTFE binder	PTFE binder

NRC Asymmetric Cell Design

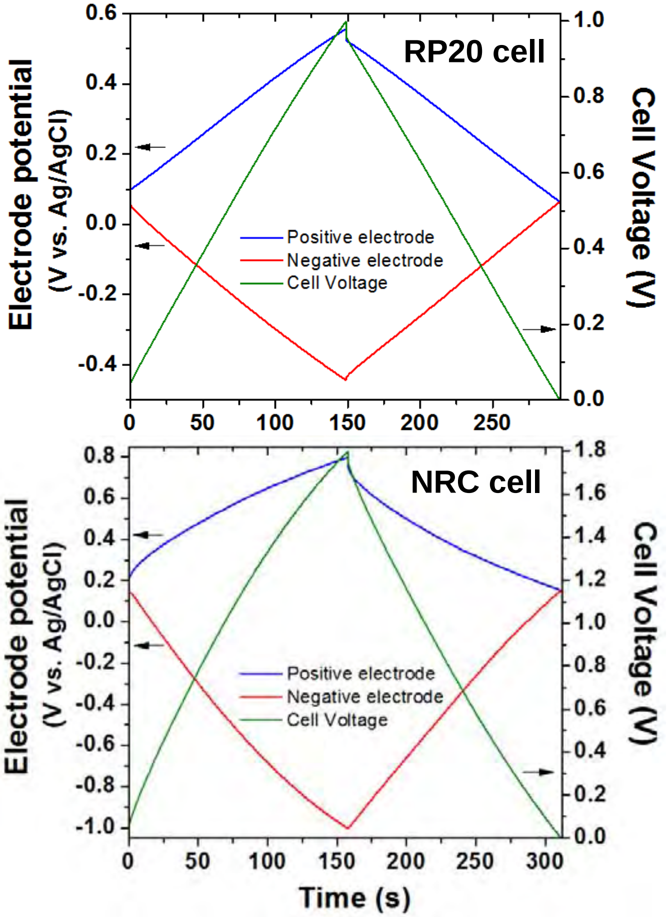
Cyclic voltammetry



- Higher voltage leads to higher capacity (energy) stored
- Lower internal resistance at the separator and current collectors
- Better capacity retention at high scan rates

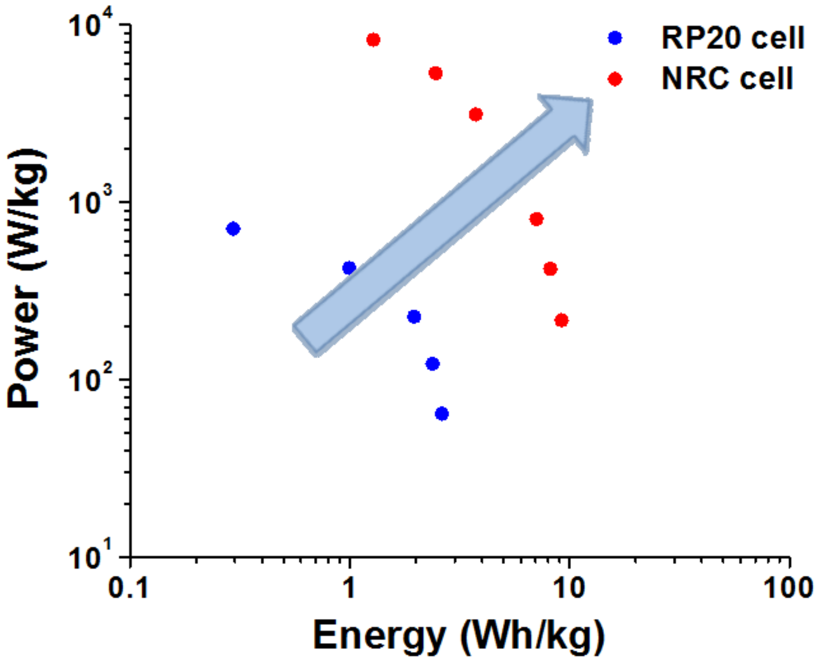
NRC Asymmetric Cell Design

Galvanostatic cycling



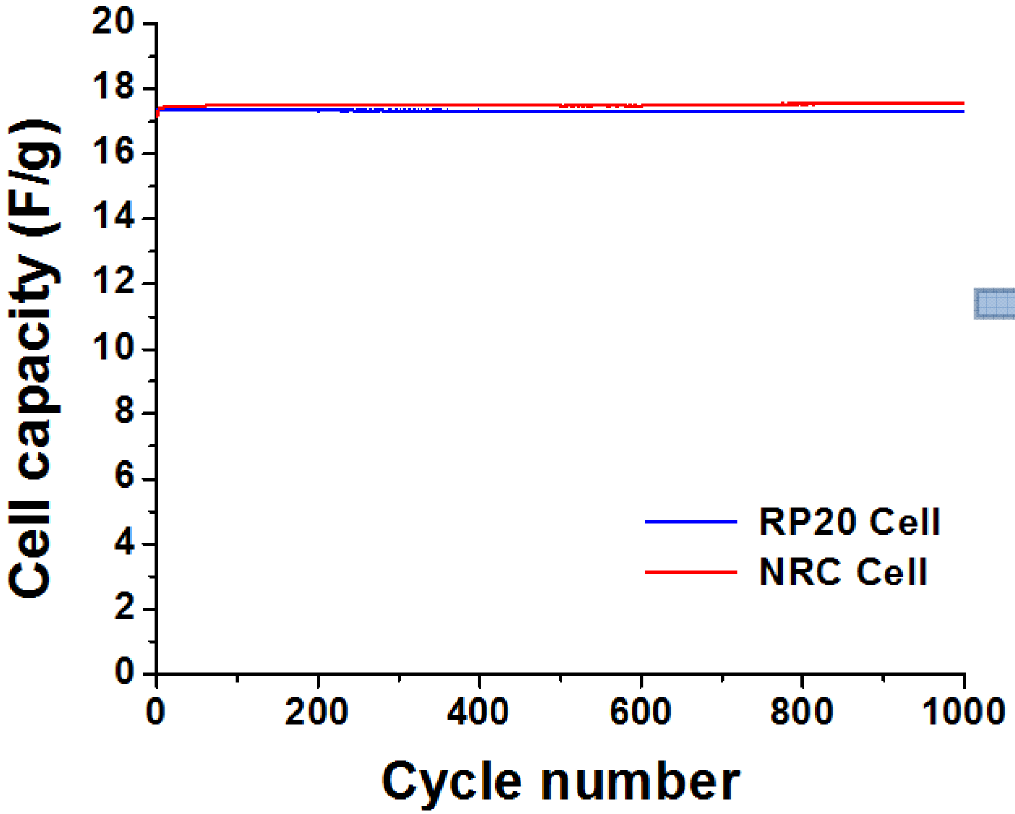
⇨

Ragone plot



⇨ **Improved energy and power output**

NRC Asymmetric Cell Design



In progress

Conclusions

The objective of the project is to improve performance of supercapacitors by the development of novel components and cell architecture:

- **Mesoporous carbons** as active material demonstrated a more open structure for better electrolyte impregnation and ion mobility (*NRC patented technology).*
- **MnO_2 as positive electrode** allowed the cell to reach a voltage of 1.8 V, increasing significantly the global performance.
- **Surface roughening of current collectors** resulted in a significant reduction of the cell resistance by improving the interface with the active material.
- **Ultraporous electrospun separators** (90% porosity) allowed a significant reduction of the electrolyte layer resistance.

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China's Largest Bus Manufacturer Selects Maxwell Technologie Efficient, Low-Emission, Hybrid Drive System

Ultracapacitors Provide Cost-Effective, Low Maintenance, Energy Storage Solution

Follow More

SAN DIEGO, Sept. 12, 2011 /PRNewswire/ -- Maxwell Technologies, Inc. (Nasdaq: MXWL) announced today that Zhengz Yutong Bus Co., Ltd. (Yutong), China's largest bus manufacturer, has selected Maxwell ultracapacitors for energy storage power delivery in fuel-efficient, low-emission, diesel-electric hybrid buses that Yutong is producing for public transit agenci worldwide.

Yutong's hybrid drive system incorporates 16 of Maxwell's 48-volt ultracapacitor modules to support braking energy recup and torque assist functions that enable hybrid transit buses to achieve fuel savings and CO2 emission reduction of approx 25 percent and reduce particulate emissions by up to 90 percent compared with conventional diesel buses.

"Ultracapacitors' ability to charge and discharge rapidly enables them to efficiently capture regenerative braking energy an provide instant power for acceleration," said Wang Feng , Yutong's overseas marketing director. "In addition, their long op life and minimal maintenance requirements in demanding public transit operating conditions make ultracapacitors a very c effective energy storage solution for hybrid buses."

"Yutong has developed an innovative hybrid drive system for efficient, environmentally friendly, transit buses and other he vehicles," said David Schramm , Maxwell's president and chief executive officer. "This opportunity to work closely with a w leader in transportation technology is helping us to better understand the requirements of hybrid-electric vehicles and cont optimizing our products to deliver world-class performance and value."

Maxwell ultracapacitors are powering some 4,000 hybrid transit buses currently in service worldwide, and are being emplo several other transportation applications, including a stop-start idle elimination system developed by Continental AG for m hybrid diesel automobiles now being produced by PSA Peugeot Citroen in Europe.

Unlike batteries, which produce and store energy by means of a chemical reaction, ultracapacitors store energy in an elec This electrostatic energy storage mechanism enables ultracapacitors to charge and discharge in as little as fractions of a s perform normally over a broad temperature range (-40 to +65 degrees Celsius), operate reliably through one million or mo charge/discharge cycles and resist shock and vibration. Maxwell offers ultracapacitor cells ranging in capacitance from on 3,000 farads and multi-cell modules ranging from 16 to 125 volts. For more information on Maxwell's ultracapacitor produc please visit our web site, Maxwell.com.

About Yutong: Headquartered in the city of Zhengzhou in China's Henan Province, Zhengzhou Yutong Group Co., Ltd. is industrial group mainly specializing in bus production. It is one of China's top 500 enterprises, with additional strategic bus activities, including construction machinery, automotive parts and components and real estate. Zhengzhou Yutong Bus Co the core enterprise of Yutong Group, was established in 1963, and now is located in Zhengzhou Yutong Industrial Park in million square-meter facility with a daily production capacity of over 170 buses. It has become one of the world's largest ar most technically advanced manufacturers of large and medium-sized buses and is China's largest producer of medium an buses.

About Maxwell: Maxwell is a leading developer and manufacturer of innovative, cost-effective energy storage and power solutions. Our ultracapacitor cells and multi-cell modules provide safe and reliable power solutions for applications in cons and industrial electronics, transportation and telecommunications. Our high-voltage grading and coupling capacitors help e ensure the safety and reliability of electric utility infrastructure and other applications involving transport, distribution and measurement of high-voltage electrical energy. Our radiation-mitigated microelectronic products include power modules, r modules and single board computers that incorporate powerful commercial silicon for superior performance and high relial aerospace applications. For more information, please visit our website: www.maxwell.com.

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Maxwell TECHNOLOGIES
Enabling Energy's Future™

ULTRACAPACITOR TRANSPORTATION SOLUTIONS

Maxwell Ultracapacitor Transportation Solutions

Carbon emissions, the depletion of natural resources, traffic congestion and the rising costs of fossil fuels are all issues pushing the world to search for alternative means of transportation. Mass-transit buses, fleet vehicles, long-haul trucks and other heavy-transportation vehicles such as trains, light rail, trams and metros, all benefit from the adoption of a hybrid power train approach with the use of ultracapacitors. Every day, in nearly 5,000 buses from China to Italy, Maxwell ultracapacitors are enabling hybrid and all-electric drive vehicles to save fuel and reduce emissions. Consequently, primary energy demand and maintenance costs can be considerably reduced.

Ultracapacitors quickly capture energy from braking and then use that energy to provide a short burst of power during acceleration and to dramatically reduce the use of fuel in a conventional internal combustion engine or battery drain in an electric/hybrid system. Maxwell ultracapacitors are compact, high-performance, have exceptionally long-life and fulfill many of the functions of batteries but with dramatically higher reliability and are virtually impervious to any climate condition.

Heavy transportation vehicles - such as trains, trams and metros - place particular demands on energy storage devices. Such devices must be very robust and reliable, displaying both long operational lifetimes and low maintenance requirements. Further, the devices must operate efficiently under harsh conditions including handling peak currents, high duty cycles and frequent deep discharging. Maxwell Technologies solved these issues with its ultracapacitor HTM125 module for braking energy recuperation and torque assist systems in trains, trams and metro transportation vehicles.

Download our Ultracapacitor Bus Application Brief

Maxwell Ultracapacitor Transportation Quick Facts:

Fuel economy 76 percent better than conventional gasoline-powered buses and 22 percent better than diesel-powered buses

Scalable for 6 to 16 liter engines

The only e-mark ultracapacitor module for transportation 2004/104/EEC

Higher resistance to heat and fire – lasts longer than batteries that may explode

A green, maintenance-free energy storage and power-delivery solution

Maxwell Ultracapacitor Transportation Applications:

Maxwell ultracapacitors can be used to complement batteries or replace batteries altogether in buses and trucks, including these solutions:

Regenerative Braking Systems

Maxwell ultacapacitors can absorb and store virtually all kinetic energy from a braking system. The emission-free stored electrical energy in ultracapacitors is then available to assist in acceleration, to reduce fuel consumption and accompanying emissions or battery drain, as well as power the air conditioner, operate power steering or perform other electrical functions. As an added bonus, regenerative braking takes most of the load off mechanical brakes, reducing brake maintenance and replacement expenses.

Start-Stop Technology Gets a Boost from Ultracapacitors

Start-stop technology enables the engine in conventional, electric or hybrid-electric delivery trucks and refuse vehicles to shut down when they come to a stop at a red light, picking up or dropping off passengers, or when sitting in traffic. Maxwell Technologies ultracapacitors then provide a short burst of energy that restarts the motor. With 100 percent reliability at temperatures from -25oC to 45oC, low lifecycle cost, and the ability to capture energy from regenerative braking. Maxwell ultracapacitors can save millions of barrels of oil as well as improve fuel economy 76 percent over conventional gasoline-only powered vehicles.

Bus and Truck Starter Systems

Maxwell ultracapacitors provide a lower cost of ownership for trucks and fleets and prevent lost down time due to no-start, overnight “hotel” loads, and are especially beneficial for heavy-duty vehicles in cold climates or that require repetitive starts. Trucks place heavy demand on energy storage devices and depend on the reliability of ultracapacitors, but the real benefit comes in removing up to three lead acid batteries, freeing up under-hood and step-well space, enabling load stabilization and preventing “brown out.” Starter systems for buses in cold climates eliminate morning idle heat up and the cost of jump starting.

As design engineers have found, batteries have high-energy capability while the ultracapacitors have high power capability. In an optimal hybrid alternative drive system, both technologies could be combined in a way that maximizes the benefits of both.

Maxwell Ultracapacitor Transportation Customer Applications:

Siemens Sitras

NYC Hybrid Buses

Voith Hybrid Buses

Maxwell Ultracapacitor Transportation Products:

Maxwell Technologies offers the most comprehensive ultracapacitor product line for the transportation industry. The time for efficient and environmentally-friendly energy storage and management has come and Maxwell’s ultracapacitor solutions have proven themselves to fulfill this requirement.

125V Heavy Transportation Module

This module stores more energy per unit volume, delivers more power per unit volume and weight, and lasts longer than any other commercially-available ultracapacitor solution. Especially designed for vehicles requiring the highest power performance available with shock and vibration immunity. (Hybrid buses and trucks)

48V Ultracapacitor Module

This module provides efficient cooling and a maximum continuous current of 90A without compromising reliability. Used primarily with hybrid buses and train engine starting systems.

16V Ultracapacitor Module

Engine starting systems for buses.

K2 Ultracapacitor Cells

A solution for hybrid train systems where the ultracapacitor is integrated into custom modules.

>> HOME > PRODUCTS > ULTRACAPACITORS > INDUSTRIES

Maxwell Technologies offers the most comprehensive ultracapacitor product line for the transportation industry. The time for efficient and environmentally-friendly energy storage and management has come and Maxwell's ultracapacitor solutions have proven themselves to fulfill this requirement. These solutions are an essential part in today's innovative, efficient hybrid system for public transportation and heavy transportation applications, allowing an increase in power efficiency and a reduction in fuel consumption and global CO2 emissions. Our commitment is to help our worldwide customers design and implement ultracapacitor solutions for existing and unique heavy-duty transportation needs.

Ultracapacitors for Transportation Systems

Every day, in nearly 5,000 buses from China to Italy, Maxwell ultracapacitors are enabling hybrid and electric drive vehicles to save fuel and reduce emissions.

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ULTRACAPACITORS

BUS APPLICATION BRIEF

REVOLUTIONIZING HOW THE WORLD MOVES PEOPLE.

Carbon emissions, the depletion of natural resources, traffic congestion and the rising costs of fossil fuels are all issues pushing the world to search for alternative means of transportation. Mass-transit buses, fleet vehicles, trains and heavy-transportation vehicles all benefit from the adoption of a hybrid power train approach with the use of ultracapacitors.

Ultracapacitors quickly capture energy from braking and then use that energy to provide a short burst of power during acceleration to dramatically reduce the use of fuel in a conventional internal combustion engine or battery drain in an electric/hybrid system. Maxwell ultracapacitors are compact, high-performance, have exceptionally long-life and fulfill many of the functions of batteries but with dramatically higher reliability and are virtually impervious to any climate condition.

Ultracapacitors:

- Breakthrough energy storage and delivery devices

Ideal for:

- Regenerative braking systems
- Start-stop systems
- Cold climate starting
- Hybrid electric vehicles:
  - Buses, trains, trolleys, light rail

Green technology:

- High efficiency with fewer CO_2 emissions
- Lead free

Used in over 4,000 buses worldwide:

- MAN
- Gillig
- New Flyer
- NYC Hybrid
- BAE Bus

Maxwell® TECHNOLOGIES
Enabling Energy's Future™

ULTRACAPACITORS

BUS APPLICATION BRIEF

Specifications

	K2 Series	48 V Modules	125 V Modules
Capacitance	650 - 3,000 F	83 - 165 F	63 F
Voltage	2.70 V	48 V	125 V
ESR, DC	0.29 - 0.8 mohm	6.3 - 10 mohm	18 mohm
Leakage Current	1.5 - 5.2 mA	3.0 - 5.2 mA	10 mA
E_{max}	4.1 - 6.0 Wh/kg	2.6 - 3.9 Wh/kg	2.3 Wh/kg
P_{max}	12,000 - 14,000 W/kg	5,600 - 6,800 W/kg	3,600 W/kg

Images not to scale.

Maxwell Technologies, Inc.
Global Headquarters
5271 Viewridge Court, Suite 100
San Diego, CA 92123
USA
Tel: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
Route de Montena 65
CH-1728 Rossens
Switzerland
Tel: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies, GmbH
Leopoldstrasse 244
80807 Gilching
Germany
Tel: +49 (0) 89 / 20 80 39 653
Fax: +49 (0) 89/ 20 80 39 651

Maxwell Technologies, Inc.
Shanghai Representative Office
Unit A2BC, 12th Floor
Huarun Times Square
500 Zhangyang Road, Pudong
Shanghai 200122, P.R. China
Tel: +86 21 3852 4000
Fax: +86 21 3852 4099

Enabling Energy's Future™

CAF CORPORATE

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Home / R and D / ACR System / General Description

R AND D

- AVI-2015 Project
- Ecotrans
- All-round tilt system (SIBI)
- Universal shifting rolling system (BRAVA)
- COSMOS System
- ATMS system
- ORION system
- Communication Systems
- Electric Traction System
- ACR System
- Technological simulations
- AURA: Intelligent maintenance and diagnosis system
- Data acquisition hardware (SCLAR and ASLA)
- Advanced fleet control: MAPTRAIN
- Software Services

PROYECTS AROUND THE WORLD

R and D

ACR System

General Description

- General Description
- Advantages
- Concept
- Technology
- Characteristics
- Operation

The ACR project developed by CAF in conjunction with Trainelec (a CAF group company), is an on-board energy storage system based on the use of ultracapacitors which enables trams to run between stops without catenaries, as well as to save energy through the full regeneration of braking energy.
This system is compatible with other technologies and suitable for use on rolling stock of any type and manufacturer, and on new or existing facilities and infrastructure.

- Efficient and energy saving in catenary powered operation
    - Energy saving and reduction of current peaks in catenary powered operation.
    - Maximum energy regeneration from braking processes.
- Safe running range in emergency situations in the event of sudden power failures.
- Catenary-free Operation.
    - Temporary (1 section between stations due to power line failure).
    - Permanent (several consecutive sections between stations).
    - Up to 1000 metres of catenary-free running range, depending on route characteristics, required performance and installed capacity.

Onboard Energy Storage System with UltraCaps of Railway Vehicles

Dr. Michael Fröhlich
Bombardier Transportation,
Mannheim, Germany

Dr. Markus Klohr
Bombardier Transportation,
Mannheim, Germany

ABSTRACT

The on board energy storage system with Ultracaps for railway vehicles presented in this paper proved to be a reliable technical solution with an enormous energy saving potential. Bombardier Transportation already made a lot of experiences in this field, e.g. equipped one bogie of a prototype LRV (light rail vehicle) for the public transportation operator RNV in Mannheim with a MITRAC Energy Saver. Outstanding feature was the daily operation of the energy storage unit in daily passenger service, and this over remarkable 4 years, since September 2003. With 4 years revenue service the new technology can be seen now as reliable. The very positive experience was the base for an order to equip several LRVs with MITRAC Energy Saver, which was just placed by RNV –the best confirmation of successful experience the customer could make.

The measured traction energy saving of approximately 30% confirmed fully the former calculations. The revenue service of the prototype LRV is stopped now to concentrate fully on the new order.

Running the energy storage device on board of a tram brings additionally following benefits:

- a dramatic reduction of the peak power demand, resulting on considerable benefits in the infrastructure. In the example presented in this paper a reduction to 6 substations from original 8 substations became feasible by introducing MITRAC Energy Saver on board of LRVs
- “catenary free operation” on several hundred meters without power supply from the catenary
- catenary free city center by on board storage and recharging stations

Applying the energy storage devices in Metro systems has a similar effect as in case of LRVs. However the savings distribution in the whole system will be a little bit different. Due to higher regeneration capability of metro systems the expected share of the train propulsion saving will be lower. It will be compensated by a considerable reduction of the line losses, especially for systems with low rated catenary voltages (600V or 750V).

Very promising are energy storage applications in propulsion systems of Diesel-Electrical Multiple Units (DEMUs). These vehicles lack possibilities to use the braking energy of the train. Energy storage systems on board of DEMUs bring high fuel savings together with the corresponding emission reduction. On top of that the energy storage leads to a booster effect – extra power during acceleration from the storage, by adding the limited weight of the MITRAC Energy Saver.

INTRODUCTION

Modern LRVs and Metros have the ability to convert the mechanical braking energy of the train into electrical energy and to feed it back into the catenary or the third rail. However this energy can be only used if there are in the neighborhood of the braking vehicle simultaneously other trains with high energy demand (Note that typical LRV systems have cheap diode bridge rectifiers in the substation and can therefore not regenerate into the power grid). In cases, this requirement can’t be fulfilled the braking energy must predominantly be (useless) dissipated in the brake resistors of the vehicle converter.

The challenging alternative is to store the braking energy on the train and use it during the next acceleration of the vehicle. Bombardier Transportation has selected energy storage systems on basis of UltraCaps.

The most challenging operating conditions for storage devices on board of traction vehicles (LRVs, Metro-trains, DEMUS) are:

-high number of load cycles during the vehicle lifetime
-relatively short charge/discharge times
-high charge and discharge power values

Proposed storage technologies aiming at brake energy storage are UltraCaps or Flywheels, while batteries do not achieve the necessary load cycles, see [5,8,9]. Outstanding feature of our prototype vehicle is the operation in daily passenger service, and this even since September 2003. For pure catenary free applications further alternatives can be discussed, Batteries or a 750V ground power supply, of course not leading to similar energy saving effects, see [5,8]. Bombardier preferred UltraCaps (double-layer-capacitors) with outstanding features such as high load cycle capability, high energy density (ca. 6Wh/kg) and very high power density (ca. 6 kW/kg). For the railway applications discussed here they are seen as superior to NiMH or Li-Ion batteries and flywheels. The drawback of NiMH and Li-Ion batteries is the limited load cycle capabilities NiMH batteries have furthermore a rather poor power cycle (charge/discharge) capability. Li-Ion batteries have until now safety concerns, at least in the volumes required by railway applications. Flywheel systems achieve a similar energy density on system level, but at reduced power and at the moment with open topics on safety.

MITRAC ENERGY SAVER IN REGULAR PASSENGER SERVICE

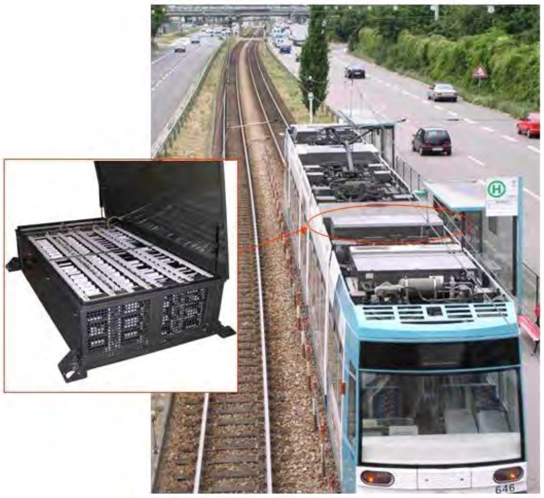


Fig. 1: Prototype Vehicle in Mannheim

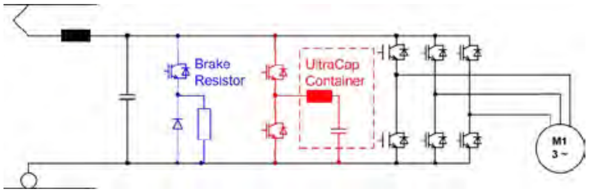


Fig 2: circuit diagram

To demonstrate the benefits of using energy storage systems on traction vehicles Bombardier Transportation equipped one LRV (light rail vehicle) with a roof mounted *MITRAC* Energy Saver (Fig 1). This energy storage vehicle has the unique feature of passenger operation, which has not been achieved by other experimental railway vehicles. Since September 2003 the vehicle has been trouble-free running in the regular passenger service of the operator RNV in Mannheim. The experimental LRV has two powered bogies with two motors each. The *MITRAC* Energy Saver unit is connected to the dc-link of the traction inverter of the powered bogie in the front (Fig 1). The inverter of the other powered bogie in the rear remains without energy storage. Such configuration of the tram propulsion system allows comparison of the energy consumption of both bogie drives and leads directly to traction energy savings.

The *MITRAC* Energy Saver system installed on the vehicle in 2003 consists of:

- a UltraCap bank with energy content of about 1kWh, with housing dimensions of : 1900mm x 950mm x 455mm and a mass of about 450 kg
- a bidirectional IGBT chopper controlling the energy flow is installed in the converter

Reduction of the Peak Power Demand and Infrastructure Losses

The current demand from the line is roughly halved by installing two energy storage units on the vehicle, see (Fig. 3). It means the MITRAC Energy Saver reduces not only the energy consumption of the vehicle but also reduces power losses in the infrastructure, which go with the square of the current.

The mass transit operator pays energy costs as well as peak power costs, both reduced by the energy storage system on board of the vehicle.

Reduction of the line current by 50% causes an identical reduction of the line voltage drop. It is obvious that UltraCap storage devices onboard of traction vehicles stabilize the catenary voltage. It can be confirmed by comparison of line voltages with and without ES in the bottom diagram of the Fig 3.

This significant advantage of system with energy storage can be exploited in different ways:

- Increasing of the distance between substations for the planned new lines

- Reducing of time intervals between following trains at existing lines
- Acceptance of longer trains on existing lines

There are also some disadvantages of the energy storage on board of traction vehicles, e.g.:

- Increase of the train mass by approximately 2%
- Additional space to accommodate the energy storage container is necessary

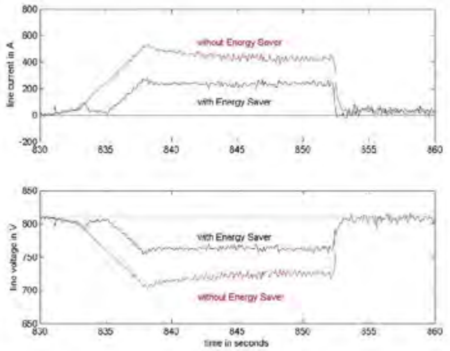


Fig. 3: Line current and voltage with and without MITRAC Energy Saver

REDUCTION OF THE INFRASTRUCTURE INVESTMENTS

In a computer simulation the influence of the number of and distance between substations has been analyzed. The chosen example is a 17,7km line with a reduction from 8 to 6 substations, when using vehicles with on board energy storage. The headway is 5 min and the distance between stations is always 680m. All the vehicles with an operational maximum speed of 60km/h are either equipped with or without a 0.76kWh energy storage device.

The following system solutions have been directly compared:

a) Line section with 8 substations, all trains without energy storage devices
b) Line section with 6 substations, all trains equipped with ES systems

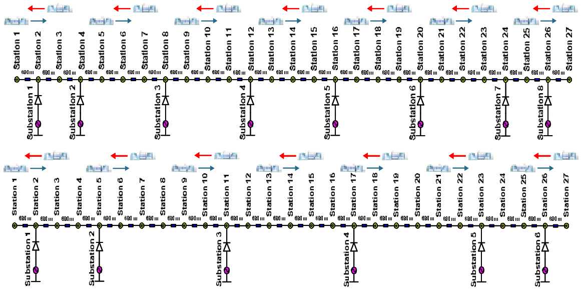


Fig. 4:. top: Reference line using conventional vehicles and 8 substations
bottom: Alternative with energy storage vehicles and only 6 substations.

The simulation results allow the following important conclusion:

The substation load currents as well as the catenary voltage drops remain in case b) despite of decreased number of substations in the same range or are even slightly lower than in case a).

Two main results were achieved by the simulation: The rated current of the substations in both cases remained in the same range as well as the voltage drop between 2 stations remained in the same region.

For example the effective values of the “Substation 2” load current are:

- **307.3A** for conventional vehicles and 8 substations
- **305.5 A** for vehicles with energy storage devices and 6 substations

The voltage drop between two substations measured on the pantograph of the vehicle is presented in Figure 5. Please note that the voltage drop during acceleration is the designing figure, see the green part in Fig 5. In both cases conventional vehicles with 8 substations and energy storage vehicles with only 6 substations the voltage drop is in the same range.

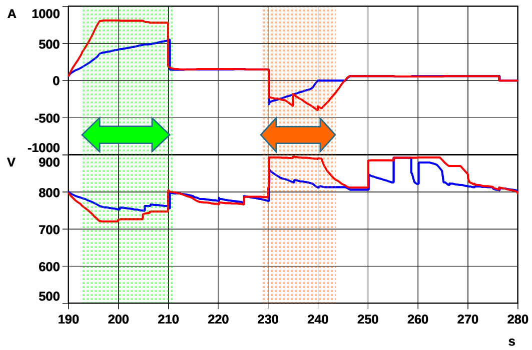


Fig 5: Line currents and voltages for trains, starting at the same time at "Station 14".
Red: casa a (trains without ES, 8 substations)
Blue: casa b (trains with ES devices, 6 substations)

The comparison of the catenary voltage curves (measured on the vehicle pantograph) for corresponding trains without and with energy storage (s. Fig 5) shows even some advantages of the solution b) with energy storage systems and only 6 substations, may be a further reduction of substations is possible. Especially the impedance voltage drop between the source in a substation and the present vehicle location is in case b) lower. This feature is very important because it results in a higher available power or lower load currents.

The trains with ES systems have better recovery abilities as well, see time between 230 and 240sec in Fig 5. Since quite a big part of the trains braking power is used for charging the energy storage, the relatively low amount of the surplus energy usually can be regenerated, utilized by other trains in the system.

In case a) the amount of energy offered by braking trains is very often higher than the present demand of other consumers in the catenary system. In such cases a part of the braking energy is wasted in the brake resistors.

The recovery of the braking energy in the own energy storage is very effective, because a big part of it will be reused locally and doesn't need to be supplied to sometimes far away consumers. It results in reduced losses in the catenary system.

With this simulation it could be proven that it is possible to reduce the number of substations by using vehicles with energy storage. This is a very important feature since the costs for substations are very high. Sometimes, especially in downtown areas, there are even problems to find an appropriate location for an additional substation.

Please note that the Return of Investment (RoI) for a new energy storage system is quite interesting. For the example of 6 instead of 8 substations and 21vehicles the RoI was below 2 years.

The RoI is very interesting from an overall point of view, but sometimes struggling with the Bid process. Infrastructure and vehicles are often handled by different departments and quite often in different stages of the project. To make use of all benefits of on board energy storage requires flexibility of all involved parties.

CATENARY FREE OPERATION

Another advantage of the on board energy storage system is the possibility to move the vehicle without external power supply. This can be used in special cases as operation during power loss but also for the so called Catenary Free Operation.

Even with limited installed energy storage of e.g. 2*650Wh, which is optimized for the energy saving effect of a 30m tram, several hundred meters could be bridged by just using the energy stored in the on board storage. In an experiment with the prototype LRV in Mannheim the train with only 1kWh installed energy covered successfully a 500m distance without power supply from the catenary. The maximal train speed was about 26 km/h. The fact, that only one bogie of the experimental vehicle in Mannheim was equipped with an energy saver makes the performance even more impressing.

This feature with limited installed energy storage allows the vehicle:

- To evacuate the track (especially tunnels) after breakdowns of the catenary power supply
- Independent movements within depots or workshops

Catenary Free Operation of an LRV is an increasing market demand. The main aspired benefit is possibility to reduce overhead wires for esthetical reasons. There are typically 2 different interests:

- Short track sections without catenary (e.g. Old Town sections or track fragments in front of historical buildings – where the building authorities doesn't allow the installation of overhead lines) This demand can be fulfilled by appropriate dimensioning of the on board storage. In most cases 2*1,7kWh installed energy on a 30m vehicle are enough. Please note that it was possible to run some 500m with the prototype vehicle which has just 1kWh installed energy

- Inner city without catenary or several sections without catenary.

This demand can be served by on board storage and recharging in stopping stations. E.g. several sections of e.g. 500m between stops

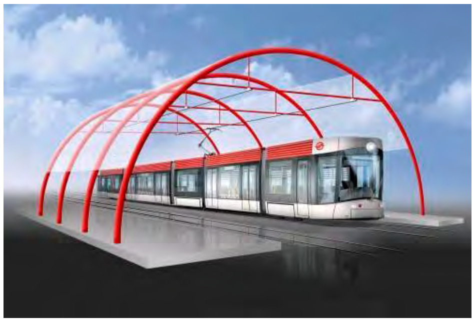
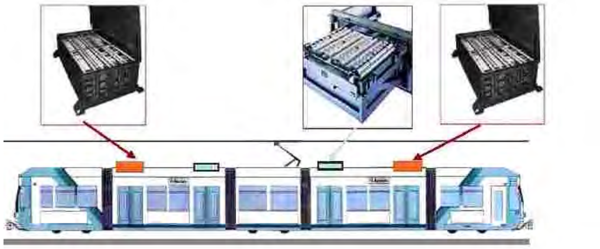


Fig. 6: Recharging station with "overhead busbar"



: Fig. 7: Availability through redundant storages, 2 MITRAC Energy Saver and vehicle battery

Recharging in the stations.

Recharging of the on board storage could be done during stops in the stations. The stopping stations should be able to deliver a power of at least 600kW. The time to recharge an energy portion of 3kWh into an on board energy storage is just 20 seconds, assuming 600kW and an efficiency of 85%. This fits very well to a 30m long tram, where the installed energy is 3,4kWh (2*1,7kWh). Please note that during the braking into the station the on board energy storage is already charged quite a bit, so that only the remaining part has to be recharged by energy from outside of the vehicle. Even in a 20 second stop there is enough time to optimize the recharging procedure to e.g. reduced overall losses. One possible realization of a recharging station could be an overhead busbar. The normal pantograph is able to handle currents up to 1kA in standstill by using the bigger contact surface of a busbar instead of an overhead wire. In this case the 600kW could be delivered from a simple recharging station by just adding an overhead busbar fed by the standard substations. LRV under catenary also have a power demand of about 600kW during acceleration.

Availability of the vehicle in Catenary Free Sections The availability of the vehicle in a catenary free section is mainly solved by redundancy of the energy storage system. A 30m long vehicle contains typically 2 independent on-board MITRAC Energy Saver as well as the vehicle battery. The following operation situations are possible:

- One failed MITRAC Energy Saver. In most of the application cases the remaining MITRAC Energy Saver can still run the vehicle through the catenary free sections by reduced performance, e.g the Aircon should be switched off and the speed might be reduced
- Two failed MITRAC Energy Saver. Even in this case the vehicle can run some 3…5 km in an emergency mode without help from outside, by using the vehicle battery. Of course the performance is very limited, Auxiliaries have to be switched off as much as possible and the vehicle speed is restricted to a few km/h, e.g. with a step up chopper from battery to dc-link to about 4km/h. The vehicle battery has quite significant energy stored, typically more than 8kWh, which should be enough for 3...5 km with limited performance. Please note that this emergency mode will nearly never happen and therefore the battery can be stressed to its maximum. For more details and a comparison battery and UltraCaps see [5]

METRO APPLICATION WITH MITRAC ENERGY SAVER

The principle of the on-board energy storage system for metro applications is very similar to the already described system for Light Rail Vehicle (LRV) [6,7, 16]

However there are some differences which can be especially for metro systems with low catenary voltages (600V or 700V) of significant importance:

- Metro systems show usually a higher regeneration ability than LRV's, especially when the line is coupled through. The reason is a big number of vehicles connected to the catenary system capable to use braking energy.
- Due to high line currents, the share of infrastructure losses in overall system losses considerably higher than in LRV systems.

Bombardier Transportation started some detailed simulations of one European metro system to evaluate the infrastructure losses and effects of high regeneration levels. The schematic diagram of the simulation model is shown in the Fig. 8. It represents a 5,4 km downtown tunnel section of the track. The average distance between substations is about 2,5 km, while the average distance between stops equals 1,4 km.

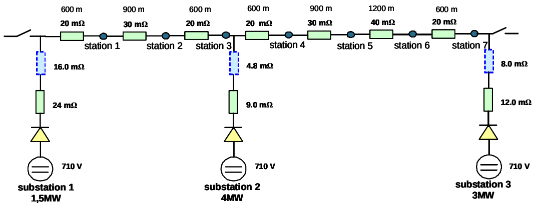


Fig. 8: Infrastructure section of a Metro system

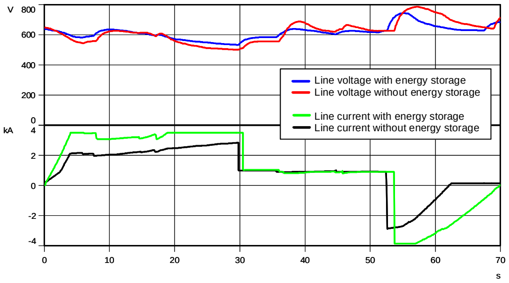


Fig. 9: Recharging station with "overhead busbar" : Simulation during the rush hour - vehicle line currents and voltages with and without Energy Saver.

The most relevant parameters and assumptions for the simulations were:

- 8 car trains with 165 t tare weight and 45 t average load
- 6 *MITRAC* Energy Savers with 1,5kWh each
- max acceleration 1,2 m/s^2, max deceleration - 1,2 m/s^2
- open circuit catenary voltage: 670 V
- brake chopper activation level: 790 V

The simulation results in Fig 9 refer to the rush hour conditions.

The bottom part of the diagram shows the comparison of line currents of the same train for two following hypothetical cases:

a) green curve - all trains in the simulated track section without energy storage
b) black curve – all trains are equipped with energy storage systems

The line current during acceleration of the train in case b) is approx. 70% of the line current in case a). It results in reduction of the line losses by approx. 50%.

Fig. 9 shows the comparison of line voltages. These rather complex curves depend not only on the temporary line current of the observed train, but is a function of the load currents and present location of all other trains in the section. In case of trains with energy storage systems (blue curve), the voltage decrease during acceleration as well as the voltage overshoot at braking is evidently lower than for trains without ability to store braking energy (red curve). The Energy Storage Units of the trains have obviously a stabilizing effect on the catenary system.

Trains equipped with energy storage systems reduce also the load currents of the substations. Especially the peak current demand will be significantly cut – see Fig. 10 (comparison of load current curves of the substation 2 during the rush hour).

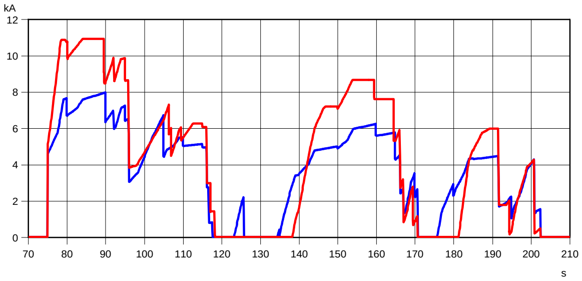


Fig. 10: top: Load currents of the substation 2 for trains without (red) and with Energy Storage Systems (blue).

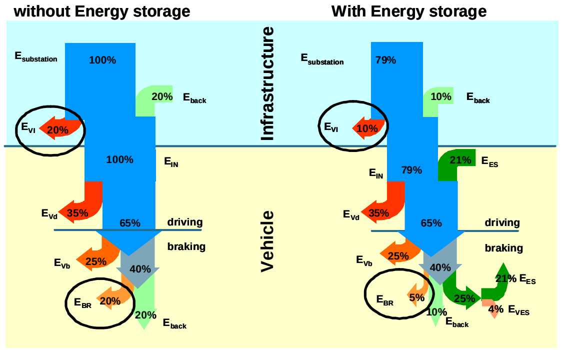


Fig. 11: Infrastructure section of a Metro system, Energy Consumption and Losses in a Metro System

The same section of the line was also simulated in the evening, where there is still a train every 4 min → 4 trains running in the section. In this case the regeneration capability is reduced, so more losses are wasted in the brake resistor or stored in the Energy Saver, while the current flow in the line is reduced, which reduces the line losses. Both effects nearly compensate each other, so the energy saving effect remains nearly constant.

A typical energy flow diagram is shown in Fig. 11. On the left side the energy flow of a vehicle without Energy Saver is shown. On vehicle level (yellow area in Fig 11) the Metro without Energy Saver takes up 100% energy from the line, there are losses during the motoring phase of about E_{Vd} = 35%, during braking of about E_{Vb} = 20%. So that the remaining braking energy of 40 % is split e.g. between losses in the brake resistor E_{BR}=20% and regeneration into the line E_{back} = 20%. In this case the regeneration is 20% (E_{back} /E_{IN} → 20% / 100%). In this example the line losses of E_{VI} = 20% are compensated by the regenerated Energy of E_{back} = 20%. The Energy supplied by the substation is 100%.

On the right side of Fig 11 the Metro with Energy Saver is presented. On vehicle level the energy taken from the line is reduced to to E_{IN} = 79%, since braking energy stored in the Energy Saver is reused E_{ES} = 21%. The losses during driving and braking are the same, while the remaining braking energy of 40% is split between reduced losses in the brake resistor E_{BR} = 5%, reduced regeneration into the line E_{back} = 10% and the storage of E_{ES} = 25% in the Energy Saver. In this case the regeneration is still 13% (E_{back}/E_{IN} → 10% / 79%). The losses in the Energy Saver are in the region of 4% (round trip efficiency 85%). In this example the line losses of E_{VI} = 10% are compensated by the regenerated Energy of E_{back} = 10%. The Energy supplied by the substation is 79%.

Figure 11 shows an example of a Metro with high regeneration, where high losses in the infrastructure are expected. In that case the energy saving effect on vehicle level as well as on substation level are both in the same region, e.g. 21% energy savings (79% consumption) as shown in Fig 11.

In Metro systems where the line is not "coupled through", or to less extend, the situation changes a bit. "Coupled through" means that the 3rd rails of several sections of the line are connected via "coupling switches", a train in one section could principally regenerate into another accelerating vehicle in another section. In a system which is not coupled through, the regeneration becomes less. Energy wasted in the brake resistors is higher while losses in the infrastructure are less.

The energy storage of brake energy on board of vehicles delivers several further advantages over and above the energy saving.

- Reduced power demand from the line – the Energy Saver delivers additional power – could result in Metro systems with less substations (less voltage drop allows bigger distance between substations), could avoid upgrades of infrastructure or could enable more or more powerful vehicles in an existing network
- Booster Effect: The additional power from the Energy Saver could also be used to "boost" the vehicle when the line current is limited.
- Rescue in tunnel, becomes possible in case of e.g. a power loss. In this case the vehicle could move to the next station by using the energy stored in the Energy Saver. Typical distance achieved is about 1000 to 1500 m from standstill to stop in a flat area, depending e.g. on the size of the Energy Saver. The principal has been demonstrated by the LRV prototype vehicle
- Feeding gaps in the 3rd rail system due to track switches or isolation between different sections in the track, could be bridged by the stored energy in the Energy Saver even without reducing the traction power
- Vehicle movement in a depot or workshop without 3rd rail becomes possible

DIESEL-ELECTRIC MULTIPLE UNIT WITH ENERGY STORAGE

There are two main reasons for using the *MITRAC* Energy Saver on board the Diesel-Electric Multiple Units:

1. The Booster Effect:
   The *MITRAC* Energy Saver enhances the vehicle performance by providing additional power for acceleration
2. Energy Saving:
   The *MITRAC* Energy Saver stores braking energy and reuses it during acceleration

It is possible to use both mentioned effects simultaneously.

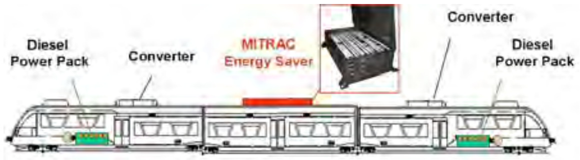


Fig. 12: Principle scheme of a diesel electric vehicle equipped with MITRAC Energy Saver

To illustrate the impact of the *MITRAC* Energy Saver on the vehicle performance, the following two versions of a typical three-car DEMU will be analyzed and compared:

- DEMU with two diesel power packs (2*315kW) and without *MITRAC* Energy Saver

- As above but with an additional 4,5 kWh *MITRAC* Energy Saver

The average weight of this train is about 100 t.

Booster effect

The main job of the *MITRAC* Energy Saver is to store the braking energy and to use it afterward for supporting the vehicle acceleration. The additional power from the *MITRAC* Energy Saver increases the vehicle tractive power and thus allows significantly higher train accelerations. In this way the energy saver compensates the disadvantage of the usually limited power of the diesel engines.

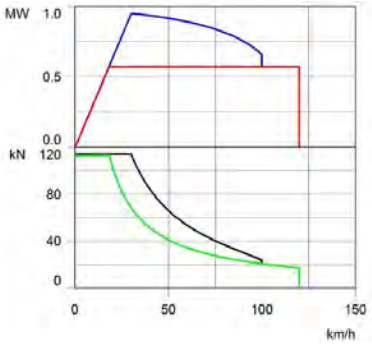


Fig. 13: Tractive power & effort curves with and without 4,5kWh Energy Saver

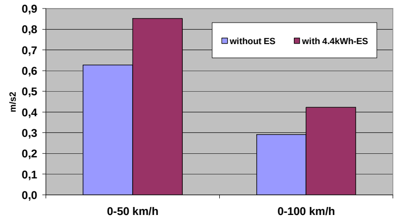


Fig. 14: Average acceleration values from 0 to 50km/h and from 0 to 100km/h

The "booster" effect of the energy storage can be very well recognized in Fig. 13. The blue curve – tractive power of the train with energy storage – lies in the speed range between 20km/h and 100km/h well over the red curve representing the same quantity of the vehicle with only diesel engines. A similar relation is valid for the tractive effort curves in the bottom part of the diagram. The comparison of the average acceleration values 0…50km/h and 0…100km/h for both train versions confirms the booster effect of the *MITRAC* Energy Saver, see Figure 14

Energy savings and emission reduction

In the previous sections a special attention was paid to reduction of the running times. However it's possible to use the booster effect thanks to additional energy from the energy storage in another way – to optimize the energy saving by allowing the same runtime, thus allowing for extended coasting.

The red curve in Fig. 15 showing a short coasting sector before braking (4% of the running time) represents the speed of a train without energy storage. The acceleration ability of the train with ES (blue curve) is much better. For this vehicle it's possible to extend the costing sector to 38% and still to achieve the same running time as the train without *MITRAC* ES.

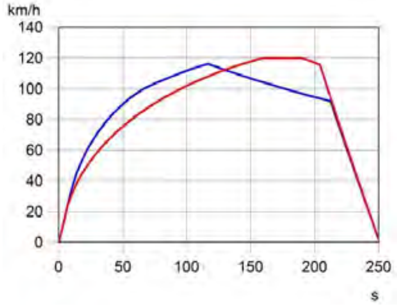


Fig. 15: Runtime simulations with and without Energy Saver. Relative fuel saving of the train with ES (blue curve): 28%

The energy consumption of the vehicle with energy storage on the 6km track is about 9kWh or 28% lower than that of the train without ES. At first glance it's amazing, that the absolute energy saving is much higher than the installed energy (4.5 kWh) of the energy storage. A rather valuable conclusion from the simulation results listed in Table 1 is the possibility to swap the 4.7% time saving for additional 18% energy saving, leading to remarkable 28% total energy savings.

6 km 4,5 kWh	Savings from energy storage Energy optimised	time optimised
Runtime Savings	0%	4,7%
Energy Savings	28%	10%

Table 1: Conversion of MITRAC Energy Saver benefits

Thanks to a long coasting not only high energy savings but also emission reductions of at least the same order are achievable. The emissions savings might be in the future at least as interesting as the energy savings. The rules of "emission trading" are heavily discussed at the moment. Additionally several railway operators took up the topic "reduction of emissions" in their strategic plans, e.g. the German railways DB announced a further 15% reduction of carbon dioxide until 2020.

The possible relative time savings thanks to "booster effect" are not as spectacular as the possible energy and fuel savings (see Table 1). However the financial benefits of time savings must be also relevant for the customers since very often high performance vehicles will be asked for.

Influence factors on the energy saving

The biggest influence factors on the achieved energy saving are the distance between station, the vehicle type, or more concrete the regeneration capabilities of the vehicle.

The shorter the distance between stations the more often the brake energy can be reused. If the top speed of the vehicle is in the same range, the energy saving effect due to reused energy remains independent of the distance, but the trains energy consumption is increased with distance between stops, therefore the relative energy saving is decreased with the stopping distance.

The biggest influence on energy saving effect is the distance between stops. Secondary effect on energy saving is gradients. Especially uphill, the energy storage gets empty at reduced distance and the diesel engines become the only remaining power source, this leads to reduced coasting effect and reduced energy savings. Gradients play also an important role in the dimensioning of the energy storage. On uphill tracks the braking energy is reduced. Assuming that the energy storage is dimensioned that at least in the majority of cases the energy storage gets fully recharged by braking the train, the maximum gradient sets with its available braking energy the limit for the energy storage size.

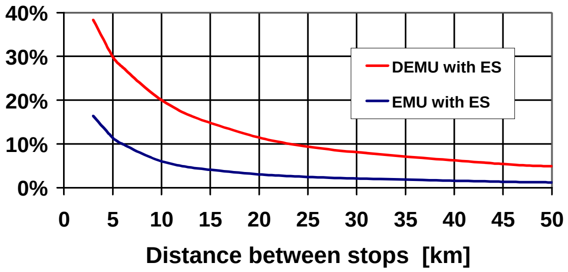


Fig. 16: Energy savings of the energy storage in function of the stopping distance for a Diesel Multiple Unit DEMU and a Electric Multiple Unit (EMU) in case of no regeneration

The energy saving effect is considerable bigger on a Diesel Electric Multiple Unit (DEMU) compared to an Electrical Multiple Unit (EMU). The main difference is that the EMU typically is more powerful and the diesel engines do not limit the available power. Therefore the booster effect is not relevant for EMUs, since there is enough power available from the line. As a consequence the energy saving effect due higher acceleration and coasting can only improve the energy saving in DEMUs. EMUs can only reuse the braking energy, which is otherwise wasted in the brake resistors. The potential energy savings of EMUs is therefore considerable below the potential of DEMUs. For EMUs the regeneration also effects the energy saving, the better the regeneration the less interesting the energy storage is. Therefore LRVs and metros with short stopping distances were focused on, but not on Main Line applications where the stopping distances are quite big and the regeneration could be quite good, e.g. in AC fed main lines.

Return on investment

In the case of the modeled three car DMU the initial investment in a MITRAC Energy Saver would be recovered in 2 to 4 years, depending on the way it is used. This estimate assumes that diesel costs between 0,6 and 0,95€/litre, and that passengers value their time saved by higher acceleration at 5€ per hour per passenger. As energy costs rise, the benefits of on train energy storage also go up.

STORAGE TECHNOLOGY

To select the best suited storage technology the requirements form the application must be known. In Table 2 an overview on the requirements from applications already described in this paper is given, as well as the requirements for a mild hybrid car, as one example from automotive area. The important application requirements are proposed size of the energy storage, which is normally derived from the average available braking energy. For the Catenary Free LRV this is of course depending on the requirements of the catenary free section, such as length and gradient of the section. Another requirement which has to be considered is the power during braking, where the storage must be designed for, to reuse most of the braking energy. For Metros and LRVs the power during braking is relatively high and drives the selection of technology, especially when the peak power is taken into account. Another value to be considered is the expected load cycles over the lifetime of the energy storage, which will be a limit mainly for batteries. A load cycle is given by charging and recharging the storage, which happens before and after each station, but also when there is a temporary stop or a speed limitation. Examples for additional load cycles between stations are traffic lights, pedestrians crossing, speed limits in curves or during maintenance work on the track. Note that also a speed limit is influencing the load cycles considerably, since the kinetic energy goes with the square of the speed. To reflect the real occurring load cycles a factor between load cycles and start stop cycles is introduced, for LRVs this factor is higher, e.g. 1,7, since in city areas several unplanned stops can happen.

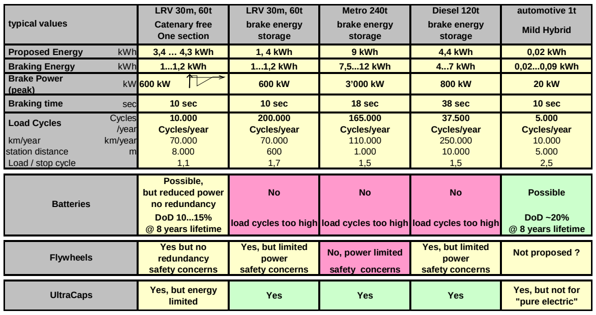
Batteries:

The main limitation for batteries for use in railway applications is the required load cycles, when aiming at energy saving due to brake energy storage. One extreme application is within LRV aiming at brake energy storage occurring each load cycle, even when only designed for 5 years 1 Mio load cycles are expected, which is too much for batteries, other storage technologies are preferred. The catenary free LRV, when using the energy storage only in the single catenary free section, is feasible with batteries. Designing the battery for 10 years lifetime this ends in 100’000 load cycles. When using a modern NiMH or Li-Ion traction battery the DoD has to be limited to about 10% (Depth of Discharge – the relation between “usable energy” and installed energy). That means that only 10% of the installed energy can be used. In automotive applications the situation is different, the limited number of load cycles is beneficial for the battery, on one hand the typical lifetime of a car which is between 8 to 12 years is less than the 30 years for railways, on the other hand the expected annual distance is considerable lower.

One relevant application where traction batteries for catenary free LRVs have been chosen is the project in Nice [14]. In this project an LRV is crossing 2 catenary free places of 400m, the power from the energy storage during discharging is limited to 200kW, while charging is only considered with even less power over long time while running under catenary on the rest of the track. The storage system weight is 1450kg. The lifetime is stated to be 5years. Please note that the storage consists of one single battery and not two redundant ones.

For catenary free applications with very tough requirements, as uphill or very long catenary free sections, the battery has the advantage that more energy can be used when allowing a shorter lifetime. Even when not preferred in standard catenary free LRV cases, since it does not allow brake energy storage and energy savings, it might be the only choice to keep the additional weight for the vehicle in acceptable limits.

The influence of upcoming Li-Ion batteries needs to be judged, when first systems in this size will be passing safety tests. The expected weight saving of more than 30% compared to NiMH is at least very interesting for Catenary free LRV applications.



typical values	LRV 30m, 60t Catenary free One section	LRV 30m, 60t brake energy storage	Metro 240t brake energy storage	Diesel 120t brake energy storage	automotive 1t Mild Hybrid
Proposed Energy kWh	**3,4 … 4,3 kWh**	**1, 4 kWh**	**9 kWh**	**4,4 kWh**	**0,02 kWh**
Braking Energy kWh	**1...1,2 kWh**	**1...1,2 kWh**	**7,5...12 kWh**	**4...7 kWh**	**0,02...0,09 kWh**
Brake Power (peak) kW	**600 kW**	**600 kW**	**3’000 kW**	**800 kW**	**20 kW**
Braking time sec	**10 sec**	**10 sec**	**18 sec**	**38 sec**	**10 sec**
Load Cycles Cycles /year	**10.000 Cycles/year**	**200.000 Cycles/year**	**165.000 Cycles/year**	**37.500 Cycles/year**	**5.000 Cycles/year**
km/year km/year	70.000	70.000	110.000	250.000	10.000
station distance m	8.000	600	1.000	10.000	5.000
Load / stop cycle	1,1	1,7	1,5	1,5	2,5
Batteries	**Possible, but reduced power no redundancy DoD 10...15% @ 8 years lifetime**	**No load cycles too high**	**No load cycles too high**	**No load cycles too high**	**Possible DoD ~20% @ 8 years lifetime**
Flywheels	**Yes but no redundancy safety concerns**	**Yes, but limited power safety concerns**	**No, power limited safety concerns**	**Yes, but limited power safety concerns**	**Not proposed ?**
UltraCaps	**Yes, but energy limited**	**Yes**	**Yes**	**Yes**	**Yes, but not for "pure electric"**

Table 2: Application requirements and preferred storage technology

Flywheels

For storage applications on board of railway vehicles high speed flywheels are still under development, see also [15]. Compared to the flywheel versions used in substation the speed was increased to 20’000…25’000 rpm, resulting in considerably increased energy density. The increase of speed is needed to reduce the size of the flywheel system to fit them on the roof of vehicles and leads to additional safety efforts and development work. The “hard” characteristics of the PM motor designed for high speeds required higher efforts within the power electronics. As an example taking a 4 pole motor with 500kW power at 20’000 rpm requires an inverter, which is capable to generate this power at a fundamental frequency of 667 Hz with limited harmonics to reduce motor losses. Adaptations in energy, power or voltage require therefore considerable efforts in developments. The limited power of flywheels under development, which are close to a product, are often too low for brake energy storage. The high speed flywheels seem to have also some open safety issues.

The only noticeable relevant application of flywheels on board of railway vehicles is the field trial in Rotterdam [14]. After some initial test in summer 2006 the status seems to be back to under development.

UltraCaps, SuperCaps or Double Layer Capacitors

For most of the onboard energy storage applications UltraCaps are the best choice. UltraCaps are much better in power capability than other technologies and allow also high load cycles. The expected lifetime even for LRV applications is up to 15 years, with as much as 3 Mio load cycles.

For some applications like the single section catenary free LRV, the energy density might be seen as a limitation, but typically it is compensated by good redundancy and power. Compared to batteries the UltraCaps allow also energy saving and several catenary free sections.

The relevant application of UltraCap based energy storage vehicles is the prototype in Mannheim, which achieved 4 years in revenue service.

Bombardier Transportation is preferring UltraCap based energy storage. Only in a few pure catenary free applications a NiMH Battery was preferred. Anyhow all technologies are followed up very carefully.

CONCLUSIONS

Compared to conventional modern Light Rail or Metro vehicles, which are already using regeneration into the line, a train using a propulsion system with onboard energy storage results in further energy savings up to 30% and a reduction of the peak power demand by up to 50%.

With the prototype Light Rail in Mannheim the benefits have been proven in daily passenger operation, the world first application in passenger service, still unique in this application field. With the good experience in 4 years daily passenger operation the new Bombardier *MITRAC* Energy Saver can be considered as a reliable proven technology. The now placed order for energy storage LRVs from RNV for the city of Heidelberg is the best confirmation of the good results achieved in 4 years field experience.

In addition to the energy savings several cost benefits due to reduced power demand on the infrastructure can be taken into account case by case. The example presented in this paper allowed a reduction from 8 to 6 substations on the presented line, thus leading to very good Return of Investment scenario.

Furthermore the on board energy storage allows an autonomous operation. Also without external power supply or even without a catenary or a 3rd rail a short distance operation can be maintained which leads to further system advantages, such as rescue in tunnels but also for the so called Catenary Free Operation. The main aspired benefit is the possibility to avoid overhead wires in some selected areas for esthetical reasons. Even several km long catenary free areas can be served by on board storage and recharging in stopping stations.

The new *MITRAC* Energy Saver is an important contribution for a more sustainable transport system, boosting the already established environmental advantage of public rail transport.

The proven energy savings of 30% by the LRV prototype and the corresponding emission reduction is in line with various local and global energy saving programs set up by e.g. European Union and major railway operators. Therefore the on board energy storage is one of the main future technologies for rail operation.

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SIEMENS

siemens.com/rail-electrification

Sitras LCU

Local charging unit for railway vehicle operation without overhead contact line

The local charging unit Sitras® LCU quickly recharges mobile or hybrid energy storage systems on railway vehicles.
The Sitras LCU may be placed at stations or stops, or may be integrated into traction substations.
Recharging takes place during dwell time.

Features

- High charging currents for charging during typical dwell times
- Concept for highest safety and availability of the complete system for operating without overhead contact line
- Based on proven products of railway electrification (Sitras-family)
- Integrated auxiliary power supply for the station / stop
- Project specific dimensioning, also for the compact type Sitras LCU-C without auxiliary power supply

Technical data *		
Input voltage (tolerances acc. to EN 50163)	[V DC]	750
Operating voltage for full charging power	[V DC]	750...900
Charging current	[A]	1,000
Charging time, e.g. a storage with 3.2 kWh	[s]	20
Auxiliary power supply for station	[kW]	30
Permissible ambient temperature	[°C]	-5...+50
Maximum operating height above sea level	[m]	1,000
Permissible environmental data acc. to EN 50124		PD4A
Dimensions of container and cable cellar **		
– Length	[mm]	4,300
– Width	[mm]	1,600
– Height	[mm]	2,800 + 750

* other values available on request
** inner dimensions plus wall thickness; dimensions may vary acc. to project specific layout

Components

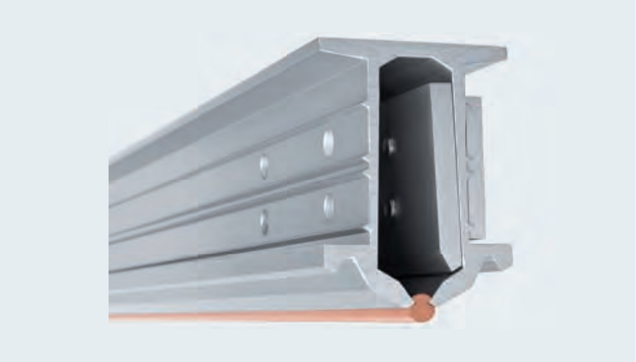
The Sitras LCU comprises the following main components:
- LCU-container with switchgear and diodes, fault protection and auxiliary power supply
- overhead conductor rails,
- cable connections to DC traction substations.

Operation

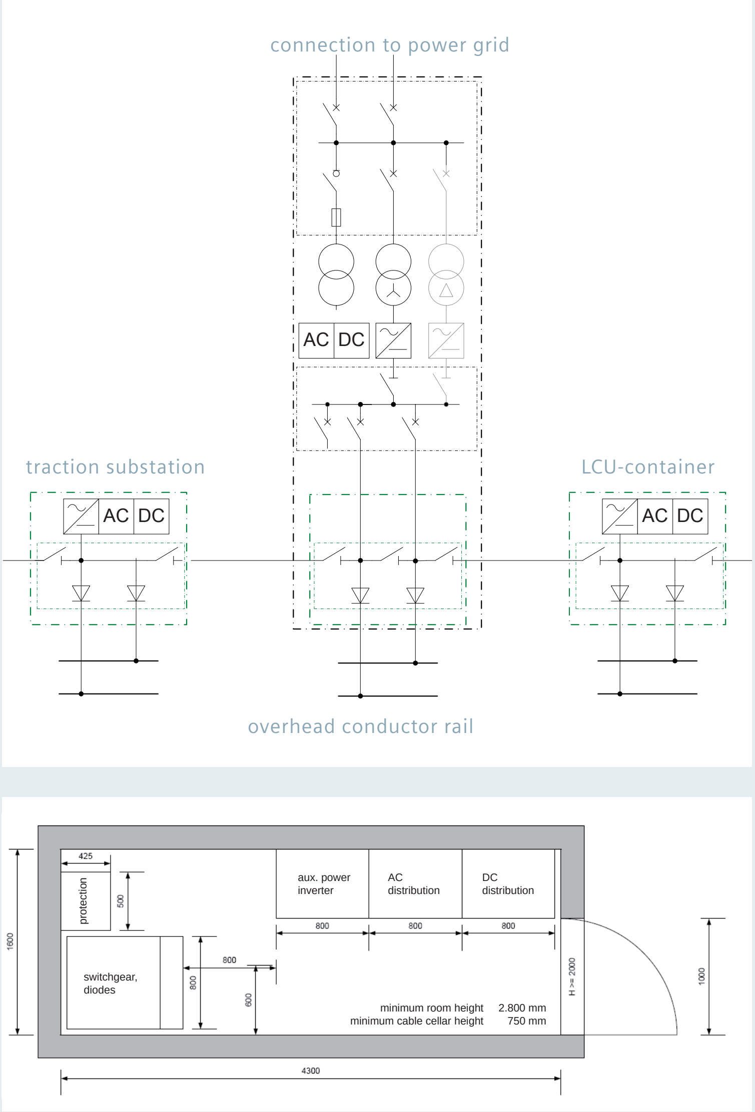
The LCU overhead conductor rails are always energized, except in case of faults. In case of failures, local control devices within the LCU and central devices in the traction substations reconfigure the system arrangement. Sitras LCU operates without active current control. The charging currents are regulated by the vehicles according to their demands.

Mechanical Design

The switchgear / diode cabinet is based on components of the compact switchgear Sitras CSG. Short circuit protection is guaranteed by Sitras PRO devices inside the LCU-container. The configuration control is realized by the station control system Sitras SCS in the traction substations. Touch voltage protection is handled by the compact short-circuiting device Sitras SCD-C. All equipment is mounted in prefabricated containers. A project dependant integration into customer's rooms is possible. The overhead conductor rails Sicat SR consist of aluminum with copper wire.



Overhead conductor rail Sicat SR



Schematic diagrams

Siemens AG
Infrastructure & Cities Sector
Smart Grid Division
Rail Electrification
Mozartstraße 33b
91052 Erlangen
Germany

electrification.mobility@siemens.com
www.siemens.com/rail-electrification

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Product Information / Version 1.0.1 / No. A6Z00031550155

The information in this document contains general descriptions of the technical options available, which do not always have to be present in individual cases. If not stated otherwise, we reserve the right to include modifications, especially regarding the stated values and dimensions.

EcoActive Technologies

‹MITRAC Energy Saver›

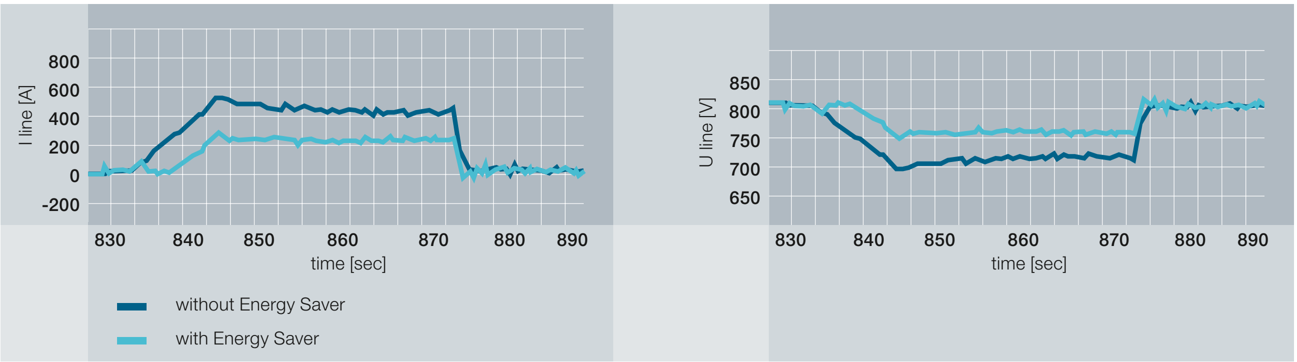
When a vehicle brakes, energy is released. To date, considerable energy has been lost in hot air. The challenging alternative is to store the braking energy on the train and use it during acceleration or autonomous operation of the vehicle.

The solution – Bombardier's MITRAC Energy Saver sets new standards

The *BOMBARDIER* MITRAC** Energy Saver works by charging up storage devices with electrical energy released when braking. The system is based on high-performance double layer capacitor technology (ultracapacitors) which allows frequent starting and braking. The stored energy can be used in many ways resulting in various benefits:

Energy savings and power supply optimization

Resources need to be deployed and utilized efficiently, in a manner that is easy on the environment – and today's rail transport systems are no exception. Environmental awareness plus reduced operating costs are now major considerations in procuring advanced rail vehicles for public transport. The benefits to customers are obvious.



Power supply optimization with MITRAC Energy Saver

The *MITRAC* Energy Saver can help reduce the energy consumption of a light rail or metro system by up to 30%! Moreover, lower peak current demand means that fewer substations are needed and they can be further apart, which reduces infrastructure investment. Using *MITRAC* Energy Saver for diesel multiple units allows energy savings by even up to 35%! Alternatively, the stored energy can be used as performance booster: the *MITRAC* Energy Saver enhances the performance of a vehicle by adding extra power during acceleration.

Performance boosting

The additional power from the *MITRAC* Energy Saver can be used to boost the vehicle's speed when line current or engine power are limited. Assuming e.g. 30% power from the Energy Saver could result in 30% higher power while keeping the same line current demand. This extra power results in additional tractive effort and allows significantly higher train acceleration. Thus, the Energy Saver compensates the disadvantage of the usually limited power of the diesel engines or increases the throughput capacity of a light rail or metro system.

Catenary free operation

The *MITRAC* Energy Saver is also the ideal solution if sections without a catenary are desired (e.g. for aesthetic reasons). The *MITRAC* Energy Saver enables catenary free operation for short distances and as a part of the *BOMBARDIER* PRIMOVE** solution also for longer distances. Additionally, the storage system makes it possible to continue operation in case of maintenance work or power failures in the grid. This can be crucial especially for rescue operations in tunnels to reach the next station allowing save evacuation of the passengers.

Benefits of the *MITRAC* Energy Saver:

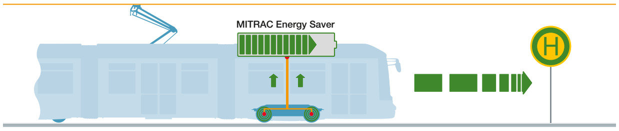
- Energy savings
- Power supply optimization, reducing infrastructure investment
- Catenary free operation
- Performance boosting

How does the MITRAC Energy Saver work?

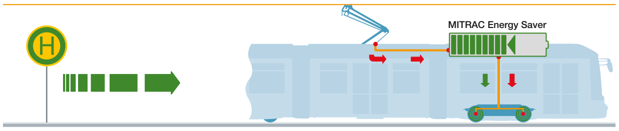
The *MITRAC* Energy Saver stores the energy released when braking and uses this energy during the next acceleration of the vehicle.This additional energy lowers current demands from the network, yet the traction effort stays the same. Measurements during acceleration up to 50 km/h show a reduction of the peak power demand by up to 50% as illustrated in the diagram above.

The technology behind

The most challenging operating conditions for storage devices on board of traction vehicles are high number of load cycles during the vehicle lifetime, relatively short charge and discharge times as well as high charge and discharge power values. In contrast to high-maintenance, flywheel-based mechanical energy storage systems, the *MITRAC* Energy Saver operates on a purely electrical basis.



Storing energy while braking



Using stored energy during acceleration

The MITRAC Energy Saver is available as a standard technical option to the new BOMBARDIER* FLEXITY* 2 light rail vehicle platform

The *MITRAC* Energy Saver solution is based on double-layer capacitors with a long service life and ten times higher performance than conventional batteries. High-performance storage cells are connected in series to create a *MITRAC* storage unit. They store the electrical brake energy with relatively low losses.

Proven technology

A prototype light rail vehicle fitted with *MITRAC* Energy Saver technology completed a four year trial period. It has been successfully tested in the system of the public transportation operator in Mannheim, Germany starting in 2003. The vehicle was in daily revenue service. The energy storage system fitted on the roof of the vehicle, proved to be an efficient and reliable energy saving technical solution. Encouraged by the success of the trial, the German operator Rhein-Neckar-Verkehr GmbH (RNV) ordered 49 *MITRAC* Energy Saver for nineteen light rail vehicles.

How much energy does it really save?

As the trial of the MITRAC Energy Saver proved, the energy savings reach up to 30% of the traction energy or 20% of the total energy demand. In consideration of the fact that the yearly energy cost for the operation of a LRV accounts around 30,000 Euro and approximately 150,000 Euro for a metro, these figures mean a high saving potential for the operators.

Beginning of 2009, RNV won the innovation prize of the State of Baden-Wurttemberg in Germany for deploying the *MITRAC* Energy Saver on their new fleet and thereby making an important contribution to climate-friendly mobility.

MITRAC Energy Saver provides performance boosting for diesel electric multiple units (DMU´s)

MITRAC Energy Saver

MITRAC Energy Saver – Applications

The *MITRAC* Energy Saver is an important contribution to a more sustainable transport system, enhancing the already established environmental advantage of public rail transport not only for light rail vehicles but also for metro systems and diesel electric multiple units. The energy saving potential is exceptionally high when the line receptivity is low and the Energy Saver is used frequently, thus if there are short distances between the stops.

The proven energy savings of 30% by the light rail vehicle prototype and the corresponding emission reduction is in line with various local and global energy saving programs set up by e.g. the European Union and major railway operators. The on board energy storage is one of the main future technologies to increase competitiveness of public transport systems by making them more economic and environmentally friendly.

Technical data

	MITRAC Energy Saver Unit		
Application	LRV 2003	LRV 2008	DMU
Installed energy (kWh)	1	1	1,17
Max output power (kW)	300	300	100
Cooling	forced air cooling	forced air cooling	natural convection cooling
Weight (kg)	477	428	466
Dimensions (mm)	1900x950x455	1700x680x450 (partly 550)	1800x1500x250
Typical application	2 Boxes for 30m LRV 2 kWh, 600 kW	2 Boxes for 30m LRV 2 kWh, 600 kW	6 Boxes for 4 car DMU 7 kWh, 600 kW

Reference projects

MVV Verkehr AG, light rail system
Mannheim, Germany
1 *MITRAC* Energy Saver prototype

Rhein-Neckar-Verkehr GmbH (RNV)
Mannheim, Germany
49 *MITRAC* Energy Saver for 19 light rail vehicles

ECO4 – Energy, Efficiency, Economy and Ecology
The *MITRAC* Energy Saver forms part of Bombardier's *ECO4 environmentally friendly technologies. Addressing the growing challenges among operators to reduce Energy consumption, improve Efficiency, protect the Ecology while making sense Economically, *ECO4* is the concrete validation of Bombardier's declaration – *The Climate is Right for Trains**.**

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Bombardier Transportation
Brown Boveri Strasse 5
CH-8050 Zurich, Switzerland

Tel +41 44 318 33 33
Fax +41 44 318 21 77

www.bombardier.com

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Next generation propulsion

and

Energy storage in railway vehicles

Michael Steiner – FEPPCON May 2004

BOMBARDIER

Une expérience extraordinaire

- Research in Energy Saving Technology
- Energy Storage Technology Options
- *Bombardier* Mitrac** Energy Saver Solution
- MVV Stadtbahn – The Energy Saving LRV
- Benefits and Vision for the Future
- Other applications

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Research in Energy Saving

- **Environmentally sound use of resources**
  - Existing resources must be used effectively and environmental friendly
- **Public and private operators under cost pressure**
  - Energy costs per Light Rail Vehicle about 30‘000 €/year
  - Energy costs of a Diesel Multiple Unit in the range of:
    - 280’000 €/year (Germany: @0,75€/liter, 250’000km/a, 1,5 liter/km)
    - 75’000 €/year (wo tax: @0,2€/liter, 250’000km/a, 1,5 liter/km)
- **At Bombardier we are also continuously investing in improving the energy use of our vehicles.**
  Our short- and middle-term solution is:
  - Storage of Brake-Energy
  - 1999 started as research topic “alternative energy supply”

Energy Storage Technology Options

✍ **Batteries:**

- Problem of loading cycles: the many starting and braking operations would require replacement of batteries after only a short time
- Starting and braking power too high for batteries

✍ **Flywheel Storage:**

- Overall height of units with this solution makes it virtually impossible to install on low-floor LRV
- Costs and safety aspects when mounted on vehicles

✍ **UltraCaps (Double-Layer Capacitors)**

- Further improved capacitor with a very high energy storage capacity
- UltraCaps are ideal for "on-vehicle storage of braking energy" applications

Energy storage technology - UltraCaps

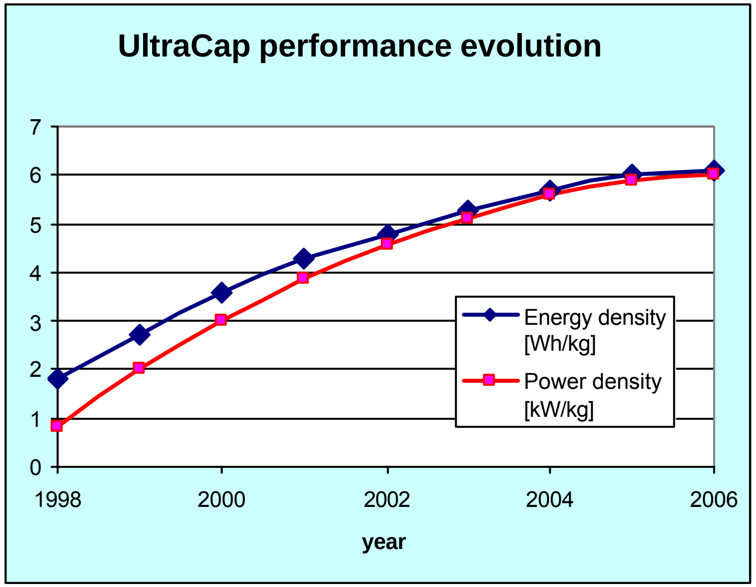
- double layer capacitors, UltraCaps, SuperCaps, ...
- Technically mature: 5 years ago the storage would have been 5 times heavier

Single cell:

2,5 V

160 in series:

400V



- Research in Energy Storage Technology
- Energy Storage Technology Options
- ***Bombardier Mitrac* Energy Saver Solution**
- MVV Stadtbahn – The Energy Saving LRV
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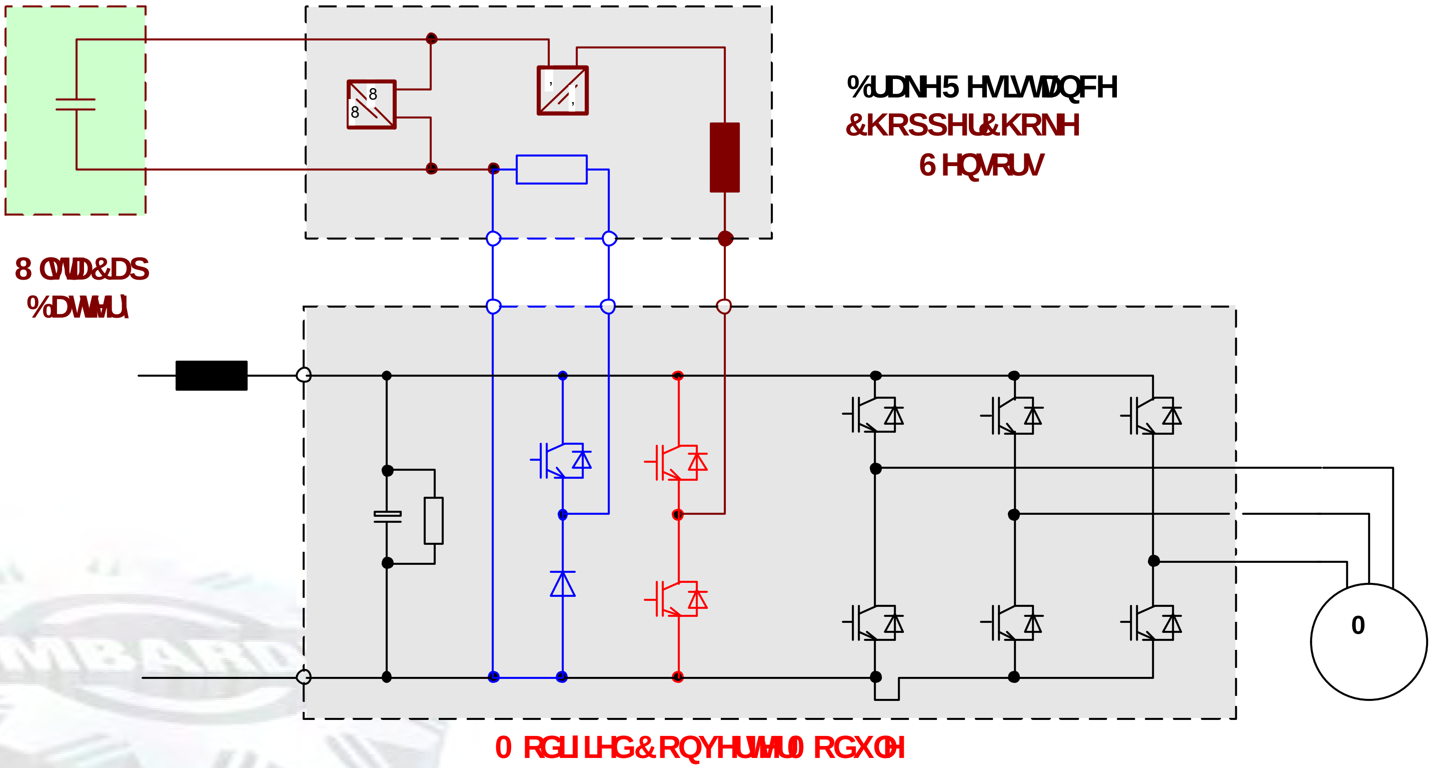
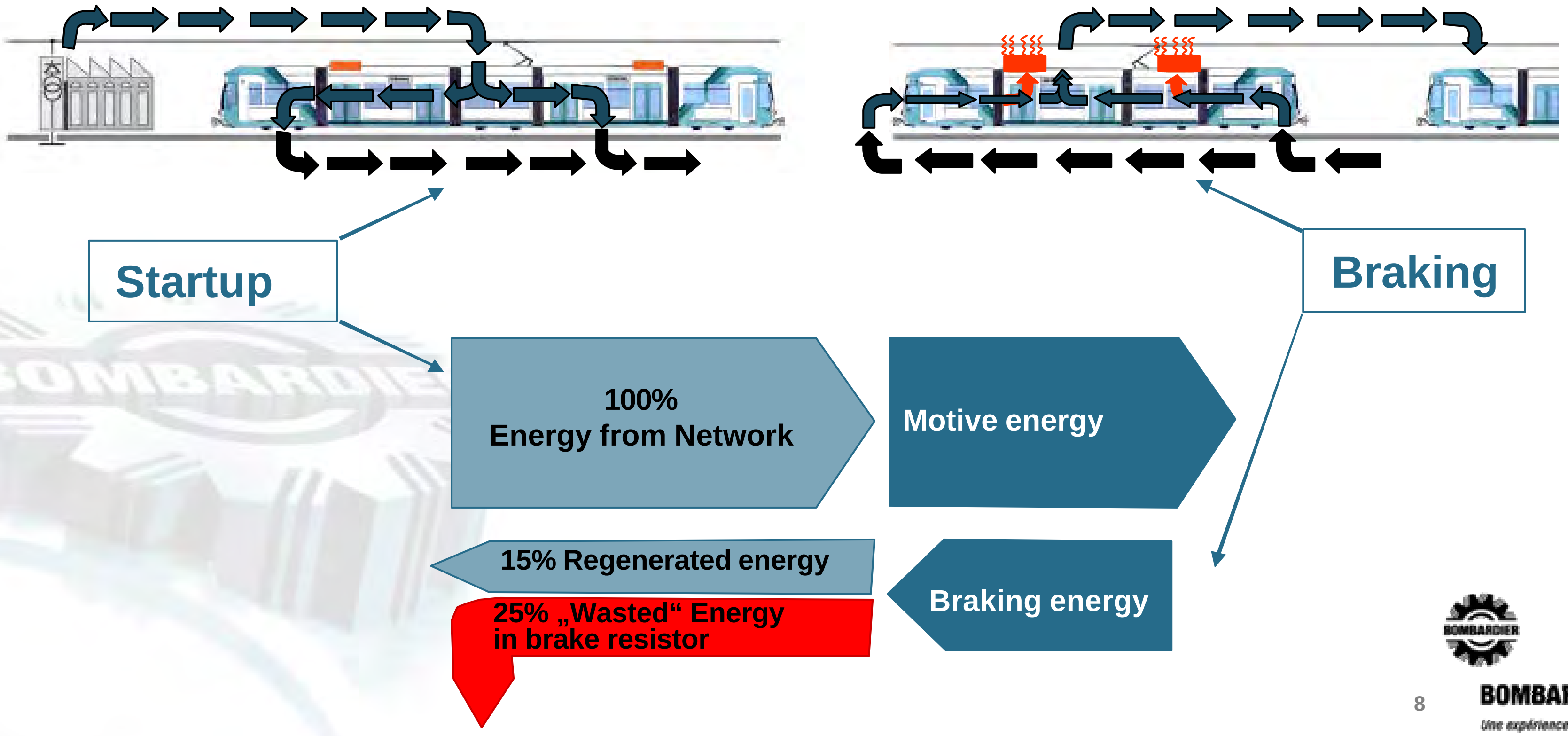
Circuit topology *Mitrac Energy Saver*



Conventional modern Light Rail Vehicles:

Braking energy

- Only around 15% of total input energy is recuperated in braking mode
- Around 25% of input energy is burned in brake resistors



Startup

Braking

100%
Energy from Network

Motive energy

15% Regenerated energy

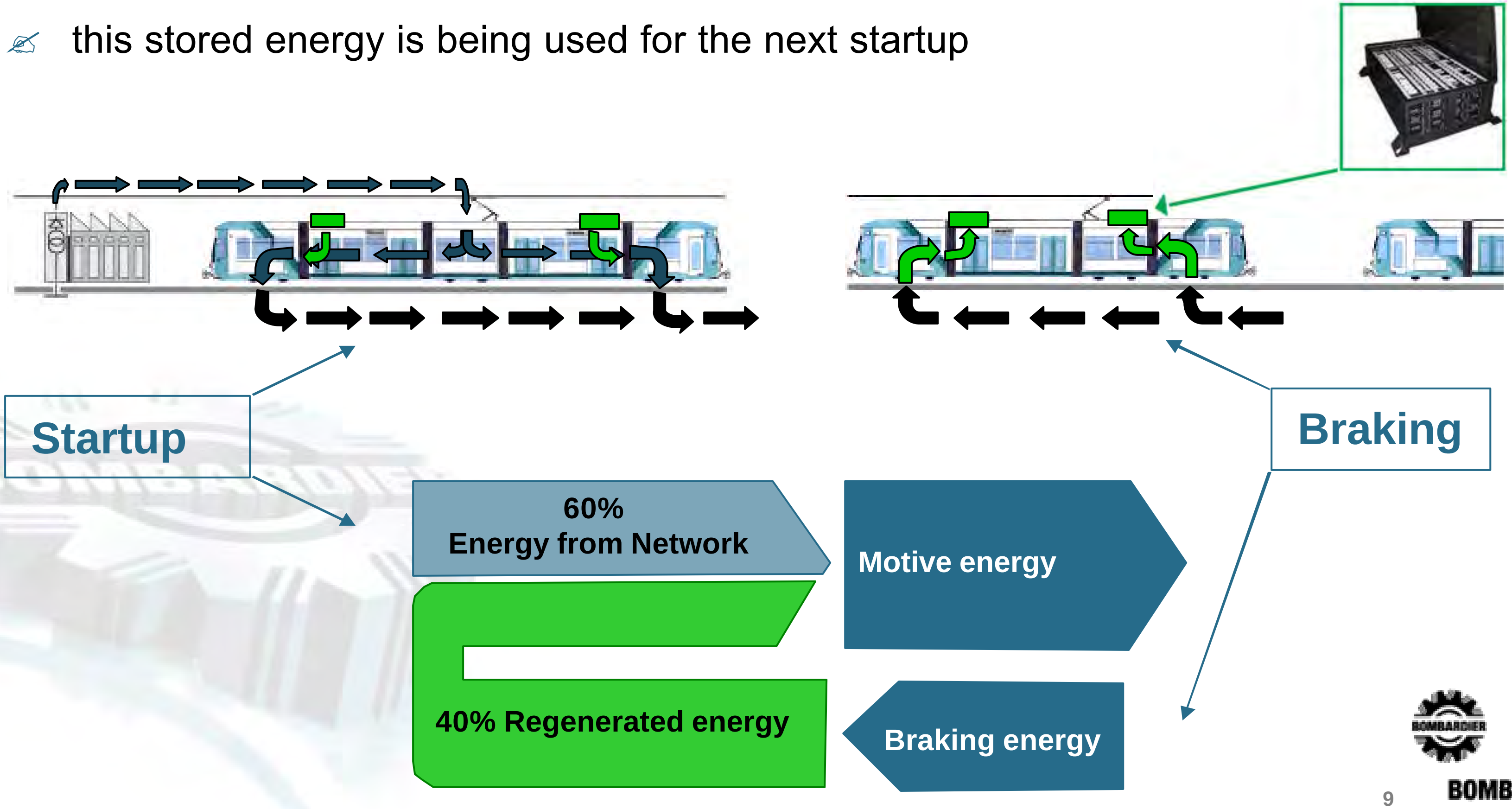
25% „Wasted“ Energy
in brake resistor

Braking energy

Mitrac Energy Saver Solution

Energy storage on board of vehicle

- Around 40% of input energy is recuperated in braking mode and fed back to the energy storage
- this stored energy is being used for the next startup



Startup

Braking

**60%
Energy from Network**

40% Regenerated energy

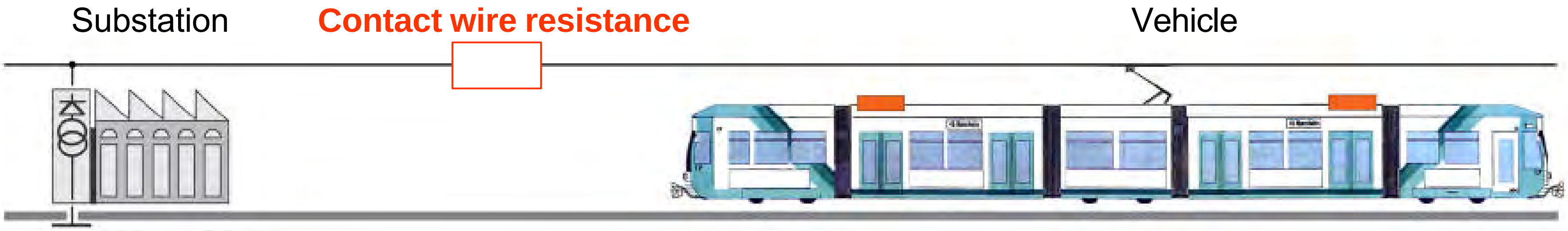
Motive energy

Braking energy

Mitrac Energy Saver Solution

Additionally: reduction of losses in contact wire

- The energy storage device reduces network current
- Lower network current generates significantly lower losses in contact wire ($P_V=R*I^2$)

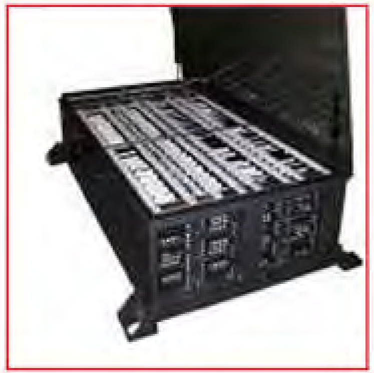


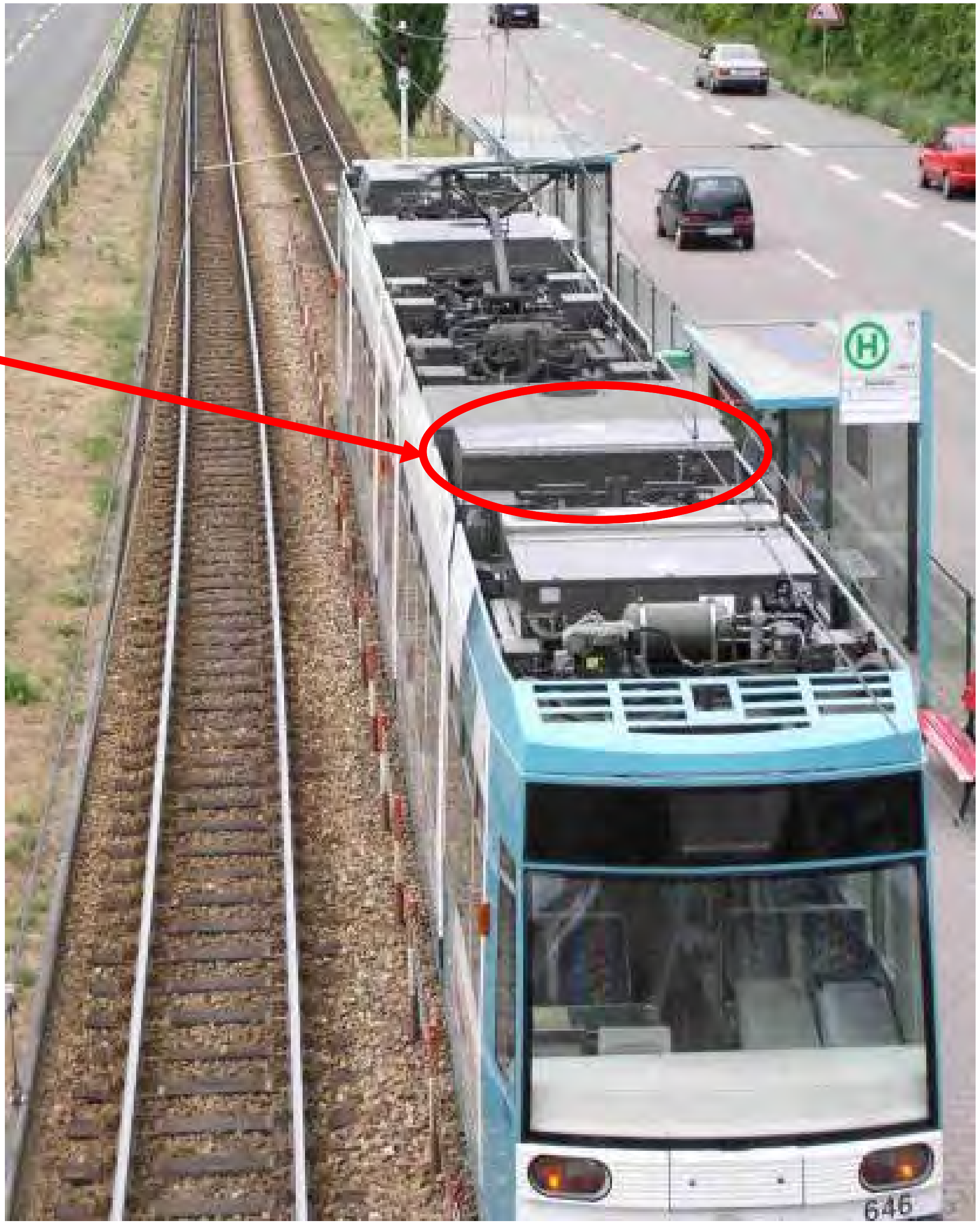
Energy saving: >5% in contact wire 25% in vehicle

Total Energy Saving: 30%
compared to a modern LRV

- Research in Energy Storage Technology
- Energy Storage Technology Options
- *Bombardier Mitrac* Energy Saver Solution
- **MVV Stadtbahn – The Energy Saving LRV**
- Benefits and Vision for the Future
- Other applications

MVV Stadtbahn - The Enegy Saving LRV





Weight: approx. 450 kg

Volume: 1900 x 950 x 455 mm

The test vehicle is equipped with one of two planned energy storage containers.

MVV LRV - The Energy Saving LRV

- Press event on 5th September 2003
- Since 5th September the vehicle is in revenue service
- good experience with new technology
- no failures in 9 month

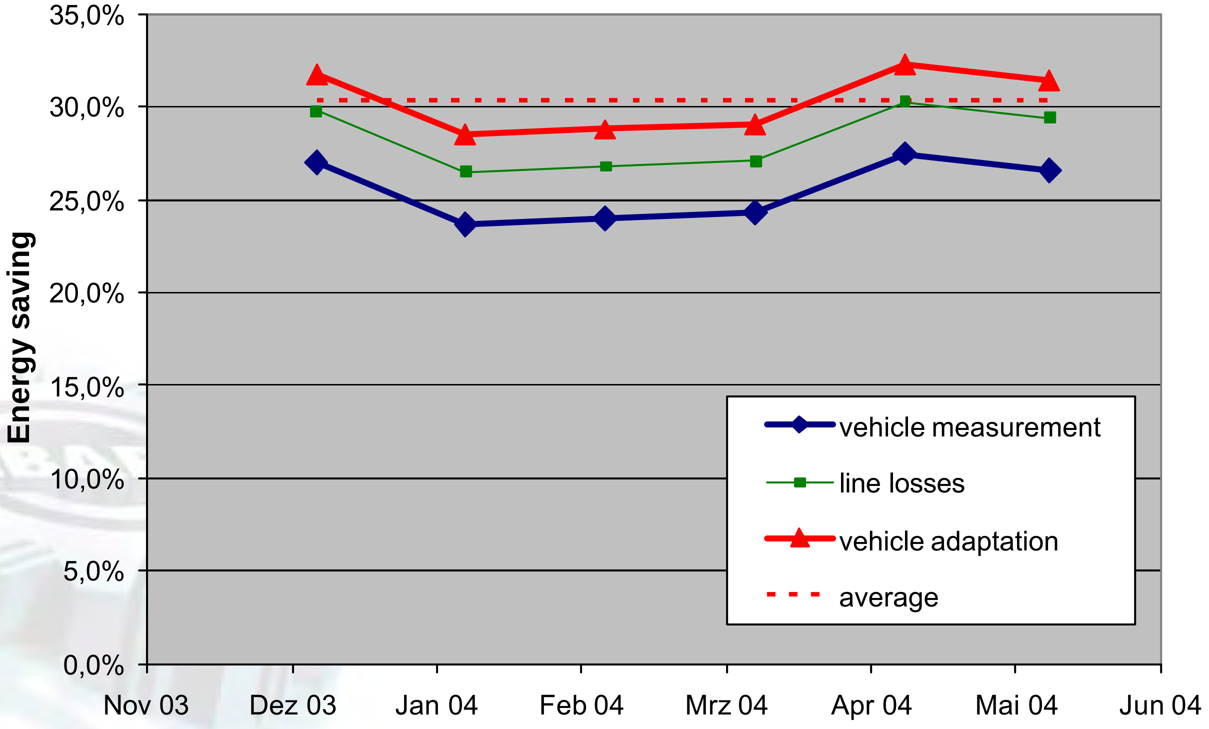
- In revenue service:
  - Experience should be gained with new technology
  - Achievement of targets should be demonstrated
  - Day-to-day operational ability should be demonstrated

MVV LRV - The Energy Saving LRV

Measurements on energy savings

✍ **between 28% and 32% depending on the climatic conditions**

MVV Prototyp



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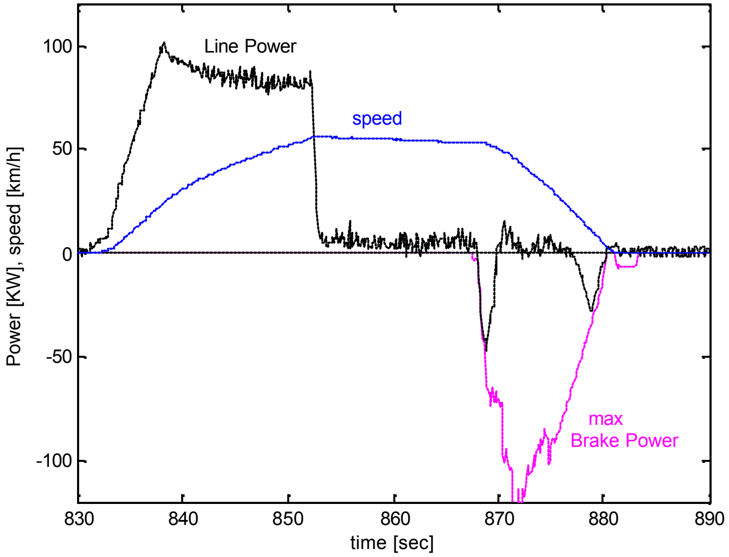
„MVV Stadtbahn“ - The Energy Saving LRV

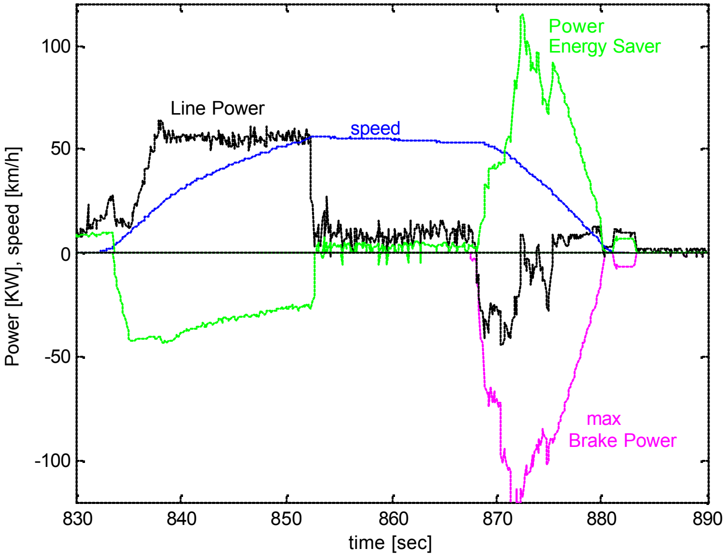
Example: Measurement 28th August

- The energy consumption could be reduced to 66% at high speeds
- the peak power demand could be reduced to 60%

Without Energy Saver

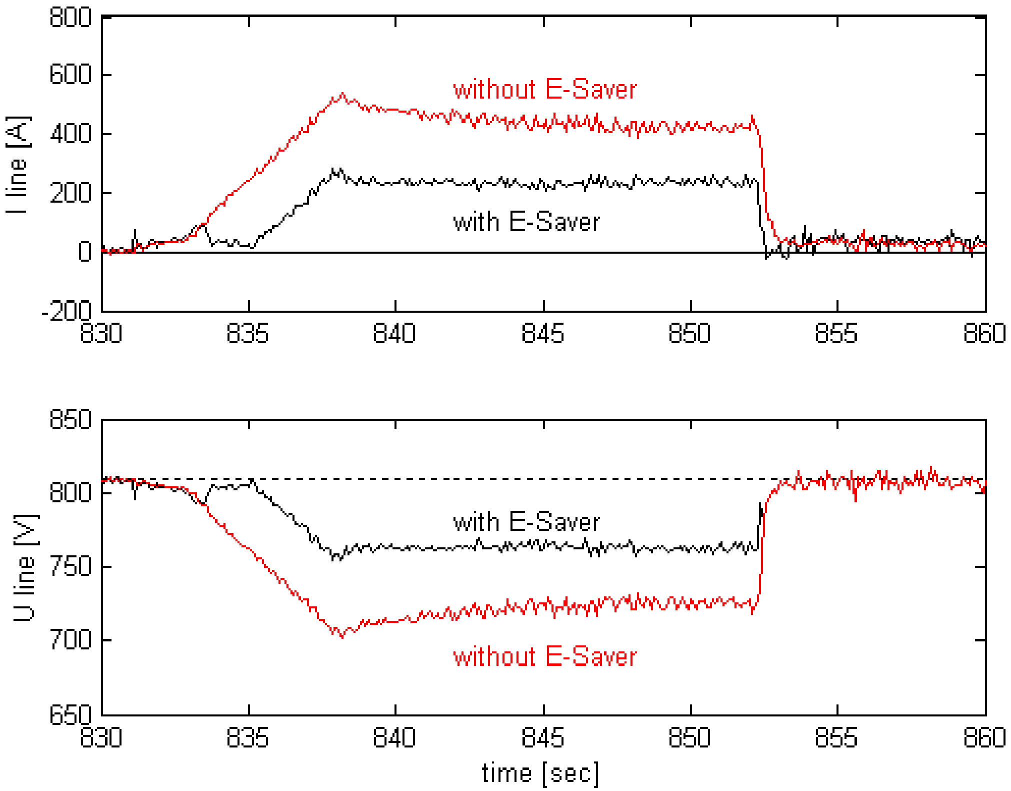


With Energy Saver



„MVV Stadtbahn“ - The Energy Saving LRV

- **With Mitrac Energy Saver the power demand from the line could be drastically reduced**
- **This reduces the voltage drop on the line as well**
- **leading to options:**
  - new lines: less substations (distance between substations increasable)
  - more vehicles in existing lines
  - reduction in cabling cross section, ...
  - on weak lines vehicles will not run in power limits



- Research in Energy Saving Technology
- Energy Storage Technology Options
- *Bombardier Mitrac* Energy Saver Solution
- MVV Stadtbahn – The Eneergy Saving LRV
- **Benefits and Vision for the Future**
- Other applications

Drawbacks of the *Mitrac* Energy Saver Solution

- **Energy storage requires space on the vehicle**
- **Additional weight ~ 2%**
  - taken into account at energy consumption
- **Additional costs**
  - price drops of UltraCaps have to be taken into account

Benefits of the *Mitrac* Energy Saver Solution

- **Up to 30% Energy saving**
- **Up to 50% Reduction in peak power to be supplied by network**
- **Up to 50% Reduction in voltage drop via contact wire**
  - Depending on the application, following benefits could be used:
    - No limited acceleration in weak networks, therefore journey time reduction
    - Fewer substation in the case of new systems or more vehicles in existing networks
    - Reduced cross section of overhead wiring, feeder cable, ...
- **Operation in sections of roads with no electric power**
  - Section can be cleared to next station in the event of power loss
  - Operational cases: disconnector journeys, icy overhead lines
  - Journeys in the depot or workshop

Catenary free operation

✍ **Some cities need to operate at least some sections of roads with no overhead line:**

  - It is difficult to obtain approval for the installation of overhead lines in front of historical buildings
  - In such cases, this solution makes the introduction or reintroduction of a light rail system much easier

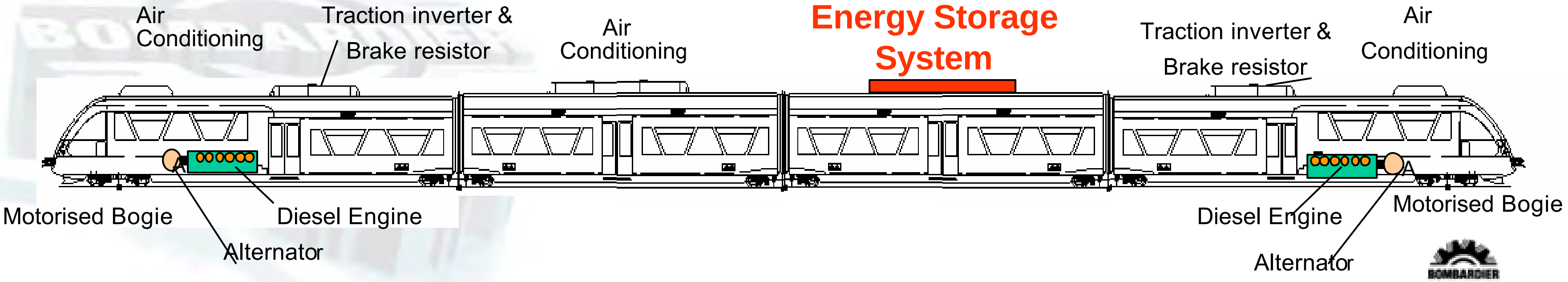
- Research in Energy Saving Technology
- Energy Storage Technology Options
- *Bombardier Mitrac* Energy Saver Solution
- MVV Stadtbahn – The Eneergy Saving LRV
- Benefits and Vision for the Future
- **Other applications**

Diesel-Multiple Units with energy storage

- **Benefits of energy storage for DMUs:**
  - energy savings (high fuel costs, e.g. in Germany ~0,75 Euro/l)
  - additional power for acceleration
  - Soft issues: emissions, noise, switched off diesel in tunnels and stations

- **Add. power to reach same performance of 3car and 4car unit**
- 3car unit (2*662kW) 10,6 kW/t
- 4car unit without ES (2*662kW) 8,2 kW/t
- 4car unit with ES 9-12 kW/t

  e.g. DEMU with ES Energy Storage (9kWh, 3.5t)



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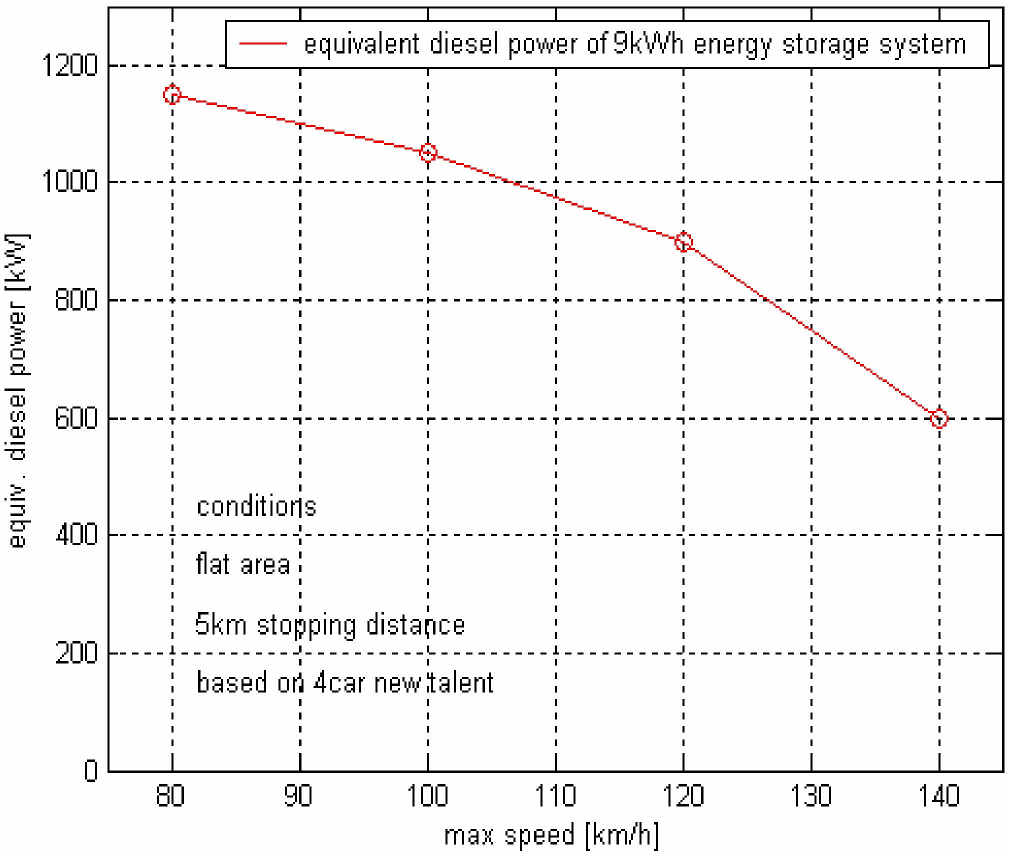
DMU vehicles with energy storage systems

Equivalent diesel power of a 9kWh energy storage:

✍ mainly influenced by maximum operational speed



BOMBARDIER
Une expérience extraordinaire

Diesel-Multiple Units with energy storage

Benefits for Diesel Multiple Units:

- **Decreased energy costs & emissions (by 25...40%)**
- **Possibility to switch off the Diesel**
  - in stations (reduced noise and emissions)
  - in tunnels (emissions)
- **Additional power from energy storage**
  - Reduction of installed diesel power (e.g. only 1 diesel engine)
  - Longer trains with same performance by additional car with energy storage
  - Flexibility to adapt to applications with limited weight impact

Next generation propulsion

and

Energy storage in railway vehicles

Michael Steiner – FEPPCON May 2004

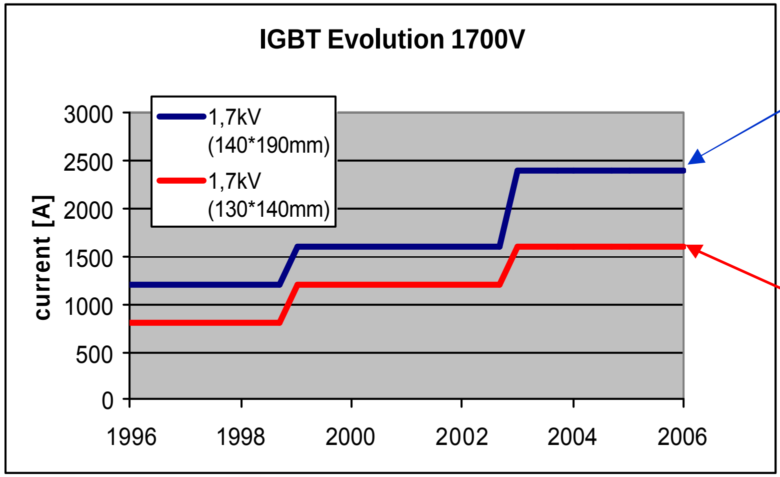
BOMBARDIER

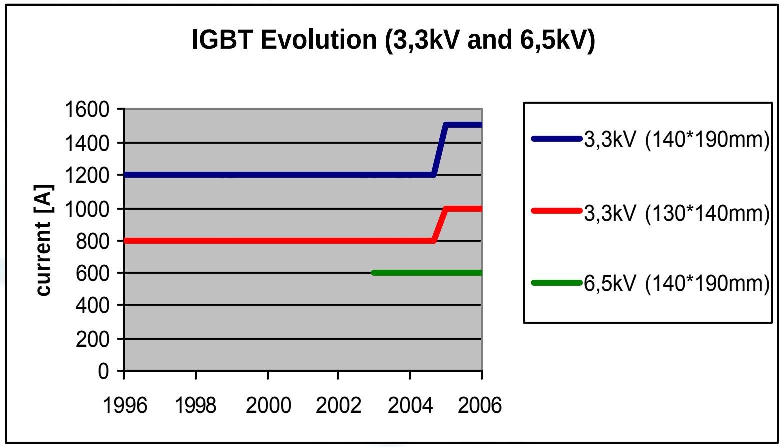
Une expérience extraordinaire

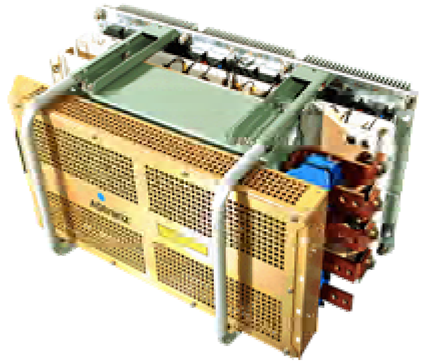
- **Overview on mid term propulsion developments**
  - **Evolution of IGBTs and Converter**
  - **Multisystem Converter (cross boarder operation)**
  - **Speed sensorless drives**
  - **Medium frequency technology**

Evolution of IGBTs and Converter

Technology Roadmap IGBTs: Increased current rating over time







IGBT 140*190 mm
for CM-I modules

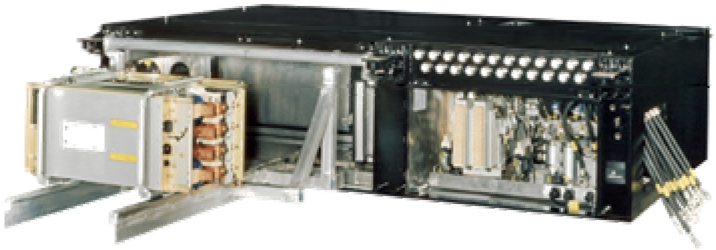
IGBT 130*140 mm
for CM-H modules

BOMBARDIER
Une expérience extraordinaire

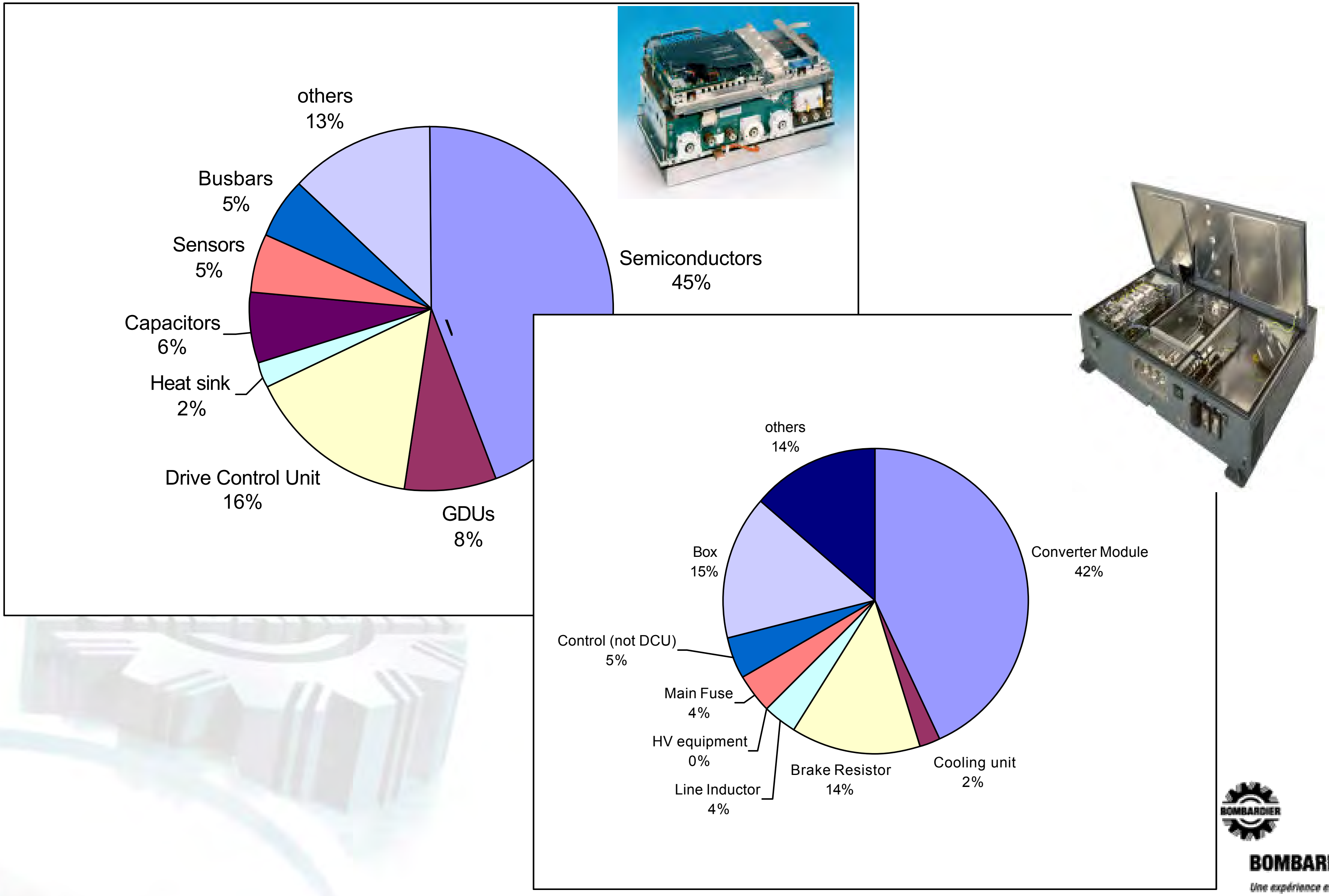
Evolution of IGBTs and Converter

Evolution of semiconductors leads to increasing converter power

- **Light Rail Vehicle with 2 motors per converter**
- **Metros/Regional trains with 4 motors per converter**



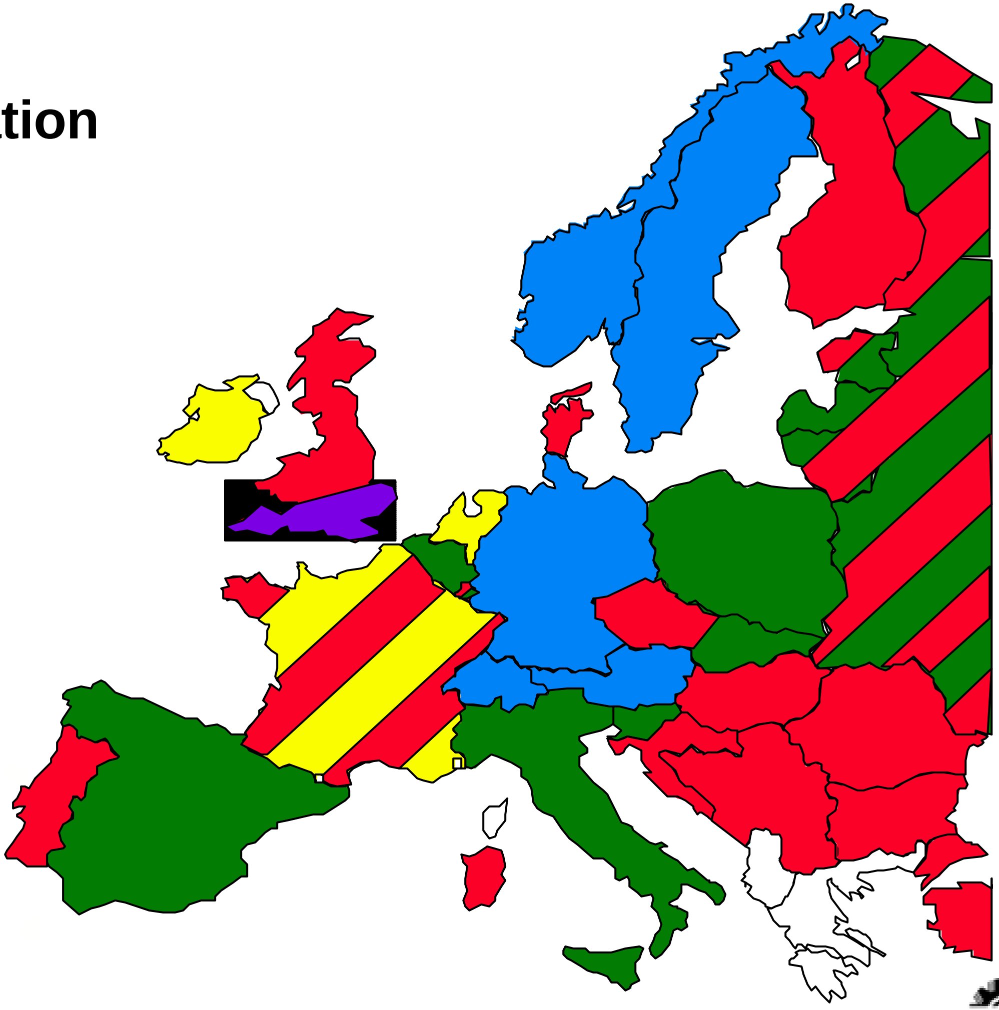
Cost distribution of converter



Multisystem Converter (cross boarder operation)

Multisystem Converter

- **cross boarder operation**
- **using 6,5kV IGBTs**



Catenary voltages:

AC 25kV / 50Hz

AC 15kV / 16.7Hz

DC 3kV

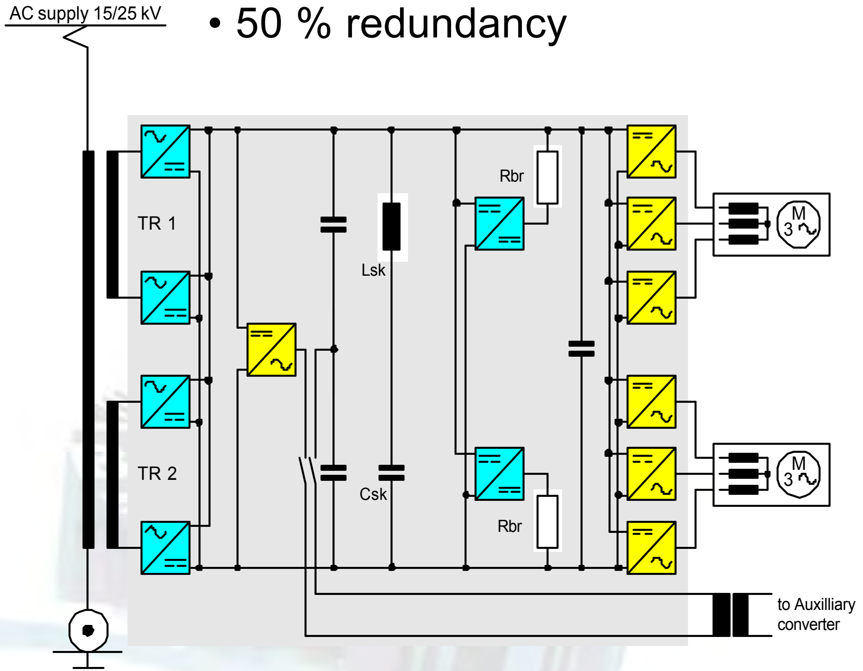
DC 1.5kV

DC 600-1200V

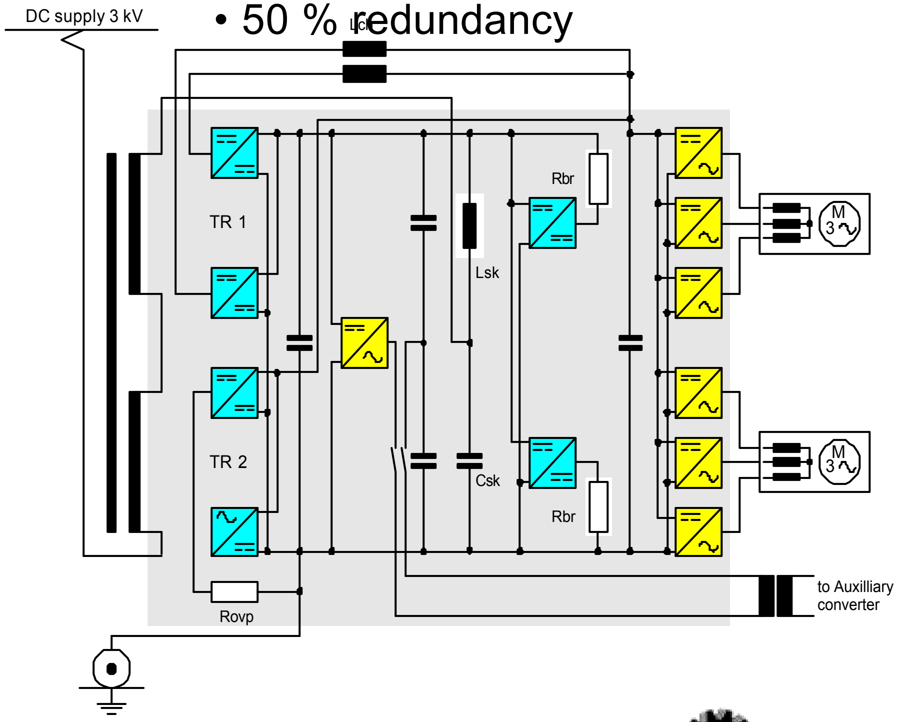
Multisystem Converter (cross boarder operation)

Multisystem Converter using 6,5kV IGBTs

AC 15/25kV
- 4 quadrant converter
- controlled 2.8kV DC-link
- 50 % redundancy



3kV DC
- step down chopper
- controlled 2.8kV DC-link
- 50 % redundancy



🟨 1 HVIM per switching function

🟩 2 HVIM in parallel per switching function

🟦 3 HVIM in parallel per switching function

Multisystem Converter (cross boarder operation)

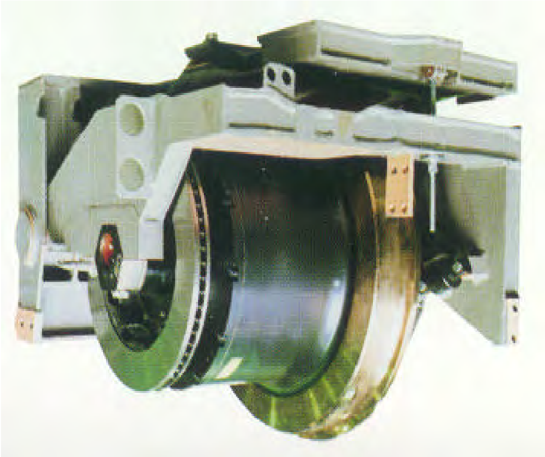
Mitrac TC3300 Multisystem converter

- CM-M Converter Module

Speed sensorless drives

Speed sensorless control of IM

- ✍ limited zero speed
  - **in 2000 applied in Helsinki tram by Bombardier**
    - **using a hub motor**
  - **Siemens presented on the EPE 2003 applications for LRVs, Metros and regional trains**



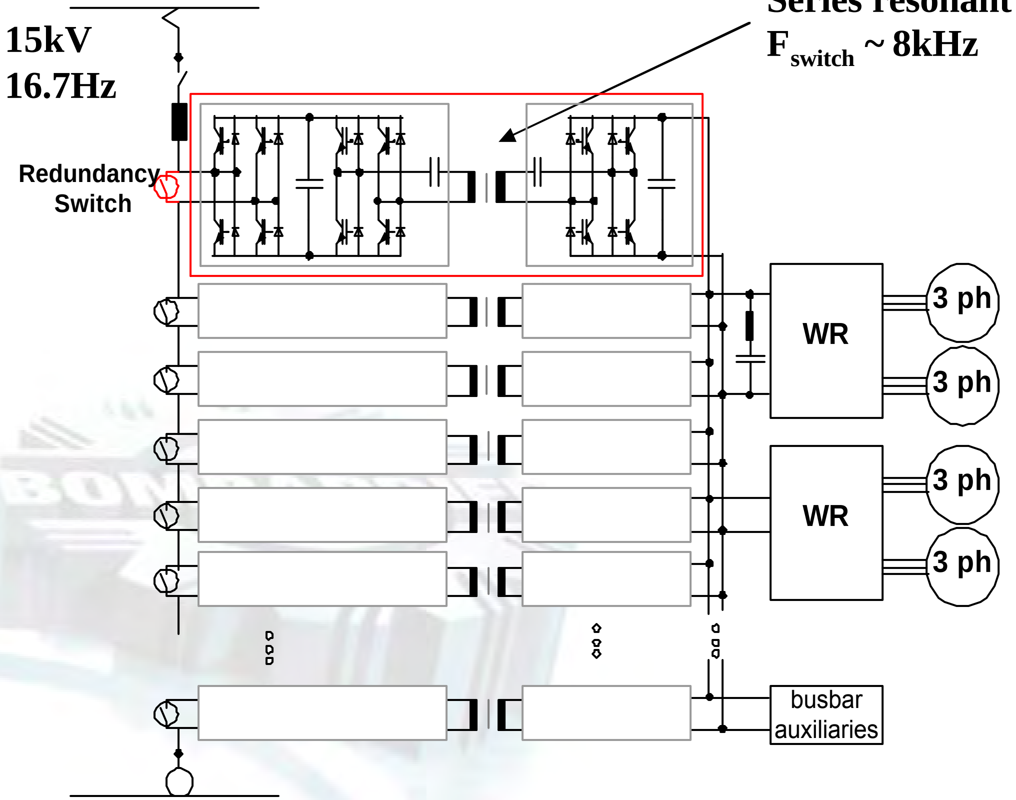
- ✍ full zero speed
  - **Research topic**

BOMBARDIER
Une expérience extraordinaire

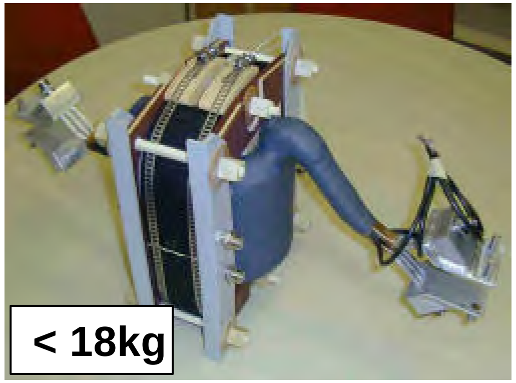
Medium frequency technology

MFT (Medium Frequency) Topology to replace the bulky main line transformer

- AC-MFT uses “electronic dc-transformers” with a considerable higher frequency of about 10 kHz



Series resonant dc/dc converter
F_{switch} ~ 8kHz



Medium frequency technology

✍ High Speed Trains

- Conventional transformer for this application are on the technical limit (e.g. ICE3):
    - maximum power with this height limit is achieved
    - very high losses of 10...12% at maximum power (50% reduced losses with MFT)
    - weight could be decreased by 30%

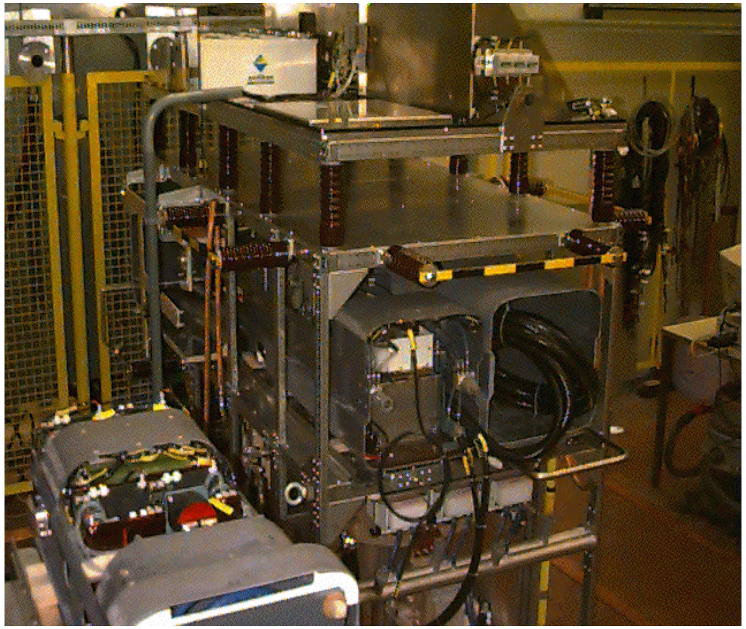
✍ Other vehicles of interest

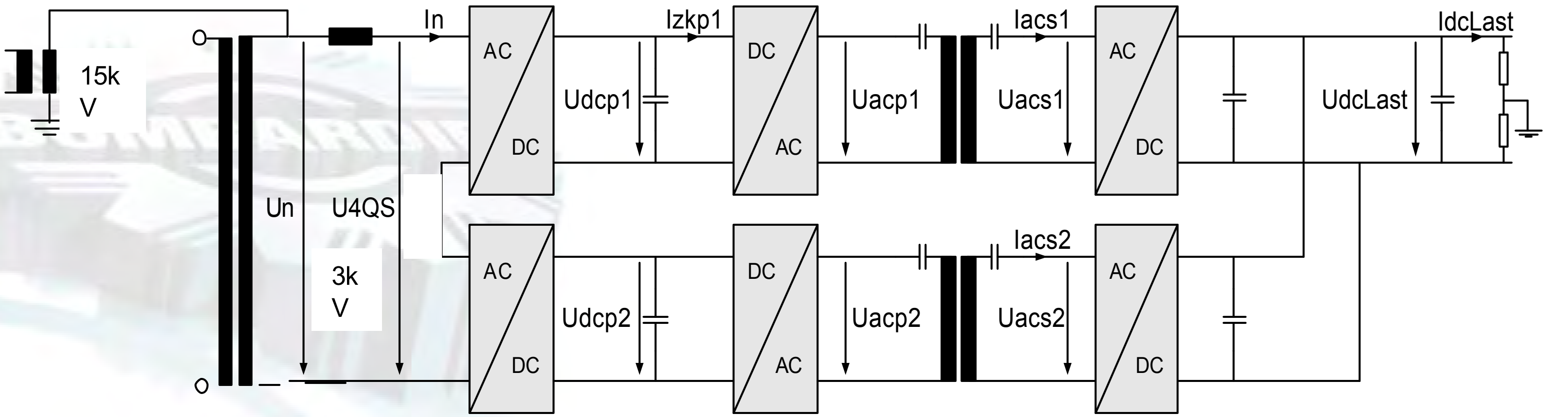
- “When weight is a problem, specially at higher power”
    - Low floor EMUs, Double Decker EMU, Multisystem Powerheads
- “Limited benefits when weight and transformer height is no issue”
    - Locos, Single system Powerheads, Single System Regional trains

Medium frequency technology

Feasibility approved

- **by e.g. high voltage lab test with two line converter modules**
- **Due to high project costs we did not develop a product without order**



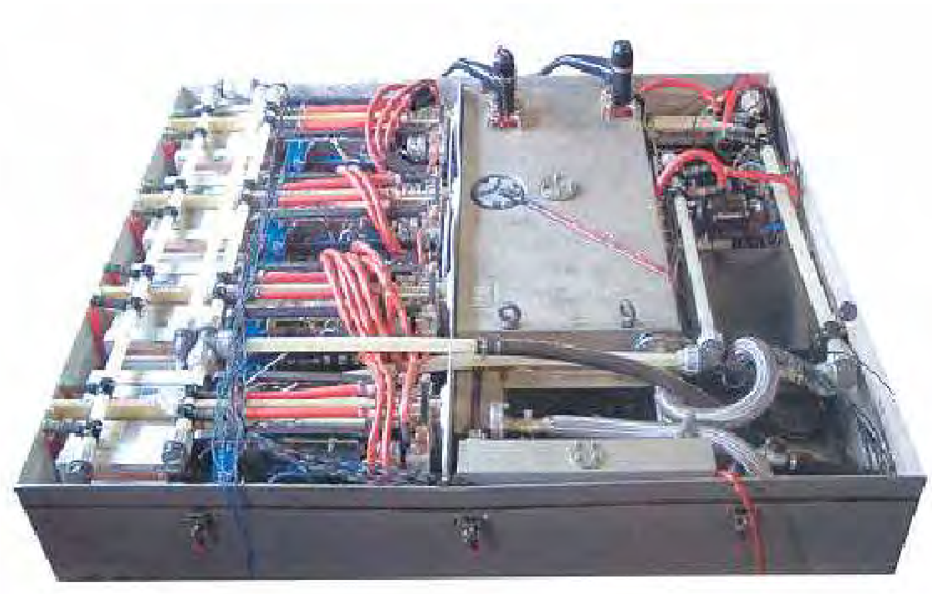


Medium frequency technology

Competitors

- Siemens worked on superconducting transformer (and MFT ?)
  - **similar benefits as MFT (weight, losses)**
- Alstom LHB build a prototype “e-transformer”
  - **very much the same as the MFT**
  - **planned for tests on LIREX (“experimental train”) in end 2004**

source: Eisenbahn Revue 8-9/2003



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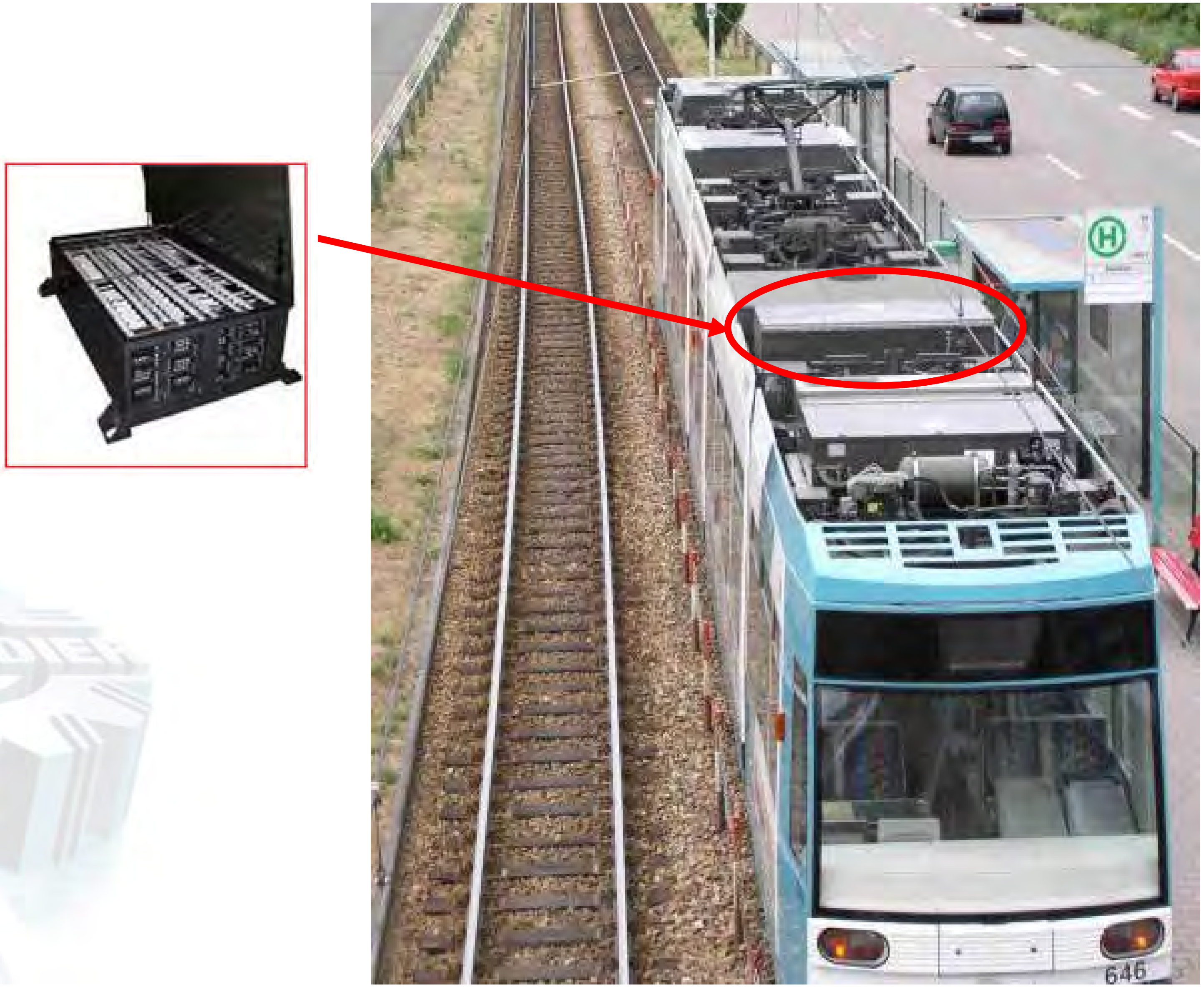


The New Seattle Streetcar With Onboard Energy Storage

Ethan Melone

Seattle Department of Transportation

Streetcar Project Manager, Seattle WA

Denny Porter / Jason Krause

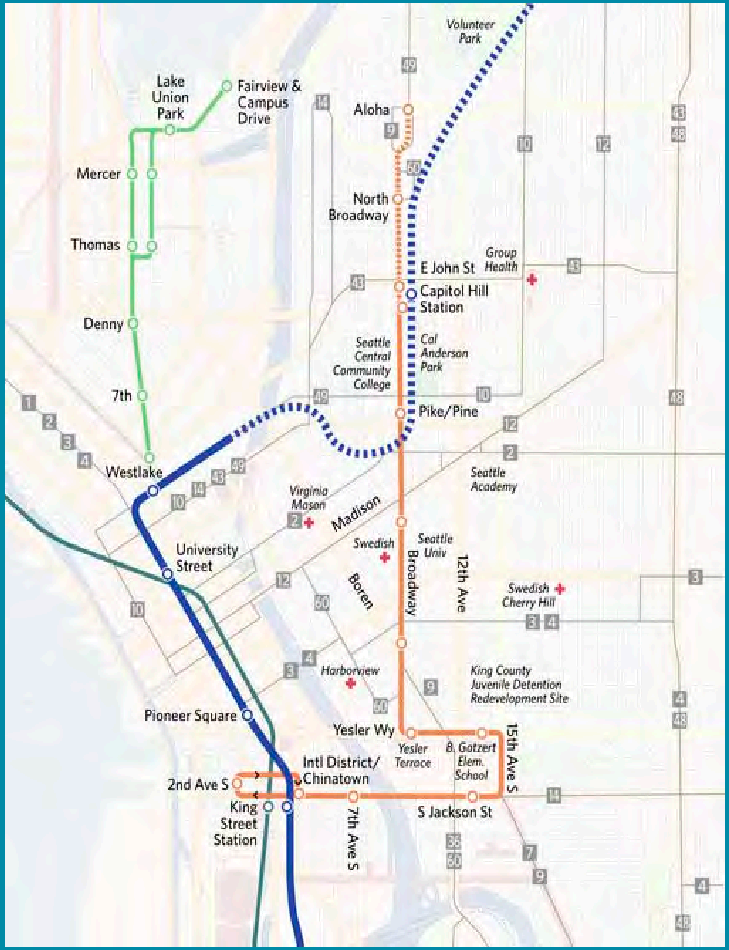
LTK Engineering Services, Consultants,
Portland OR

Overview

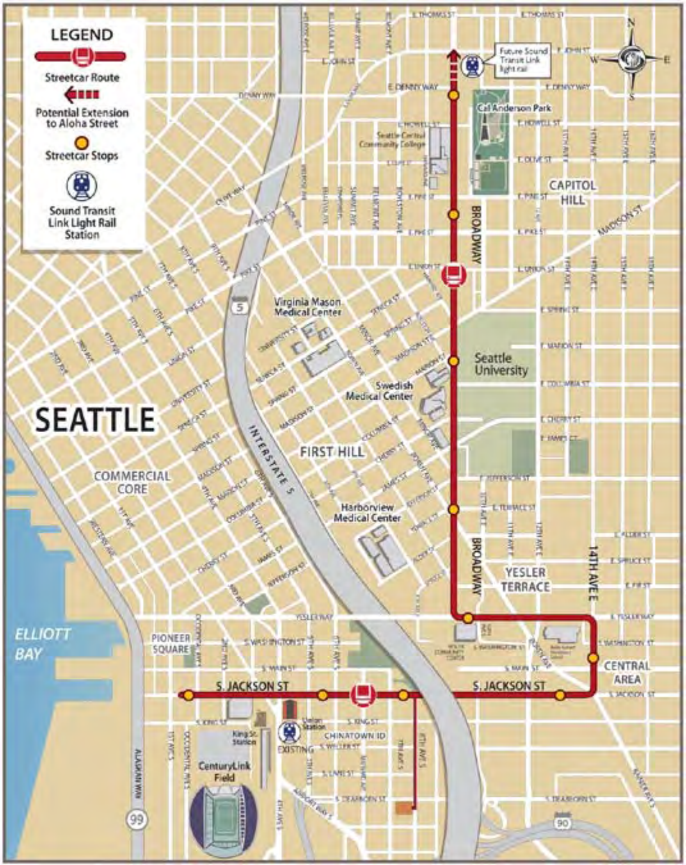
- First Hill Streetcar Project
- Wireless Operation Study
- Procurement Process
- Vehicle Description
- Schedule

First Hill Streetcar Project (FHSC)

Downtown Seattle Rail Transit



FHSC Alignment



- 2.5 miles double track
  - Average grade 2.4%
  - Maximum grade 9.0%
  - Sustained grade 3.4%
- Uphill outbound
- Downhill inbound
- In-street running
- 10 passenger stations

Wireless Operation Study

Why Wireless Operation?

- Mitigate or reduce potential conflicts
  - Electric trolley bus (ETB) overhead wires
  - New streetcar OCS
- Preserve opportunity for aesthetic mitigation of future streetcar routes
- Provide emergency recovery capability

Purpose of Study

- What is the state-of-the-art in wireless technology?
- What parameters affect sizing and capability of the hardware?
- What onboard hardware is required?
- Where are the most challenging locations?
- What locations benefit the most?
- How feasible is it?

Study Methodology

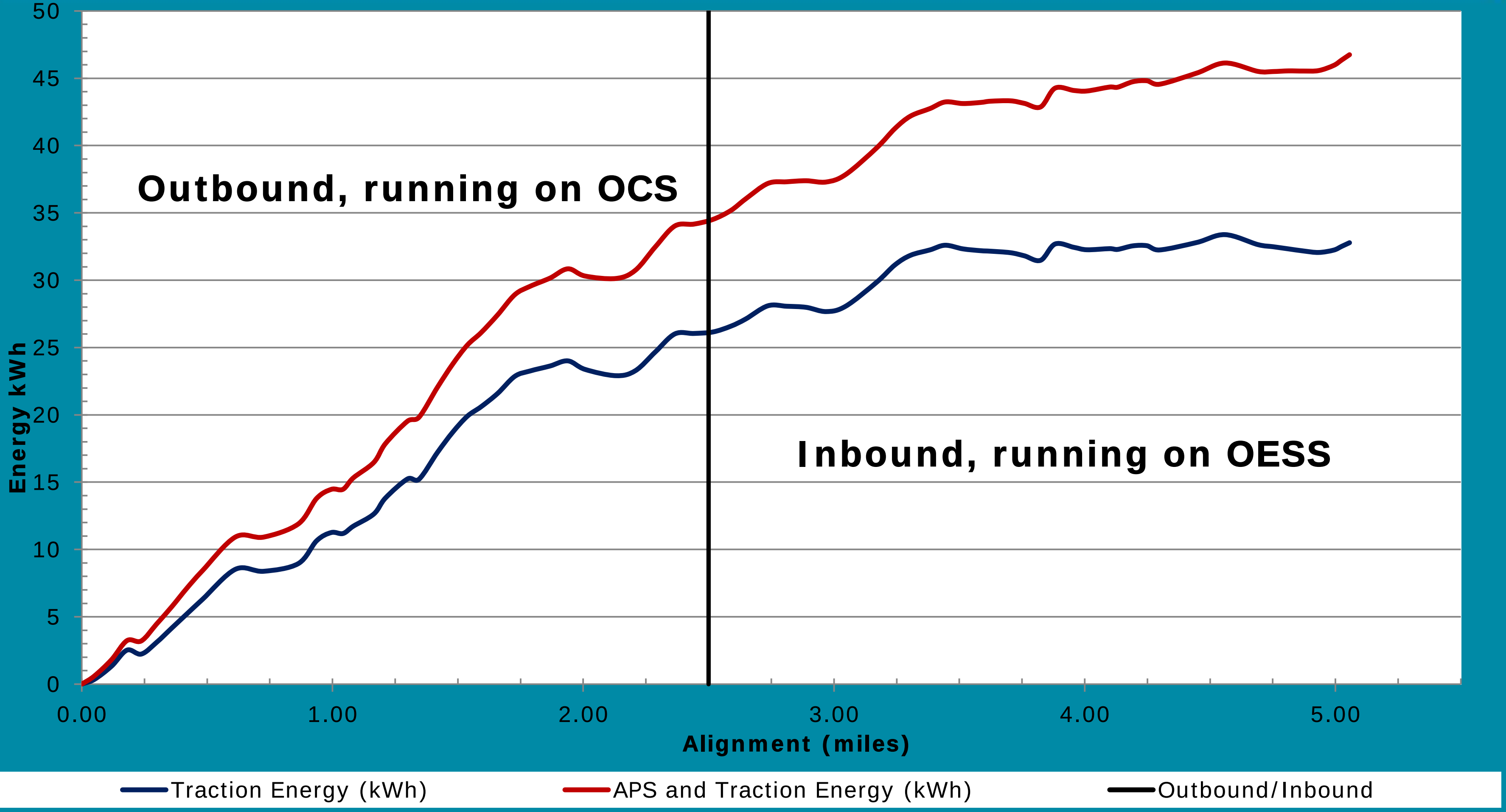
- Research
  - Current active wireless operations
  - Prototype vehicles
  - OESS types
    - Battery
    - Capacitor
    - Combination
  - OESS charging technologies
  - Industry literature

- Characterize intersections
  - Difficulty in introducing streetcar overhead wire

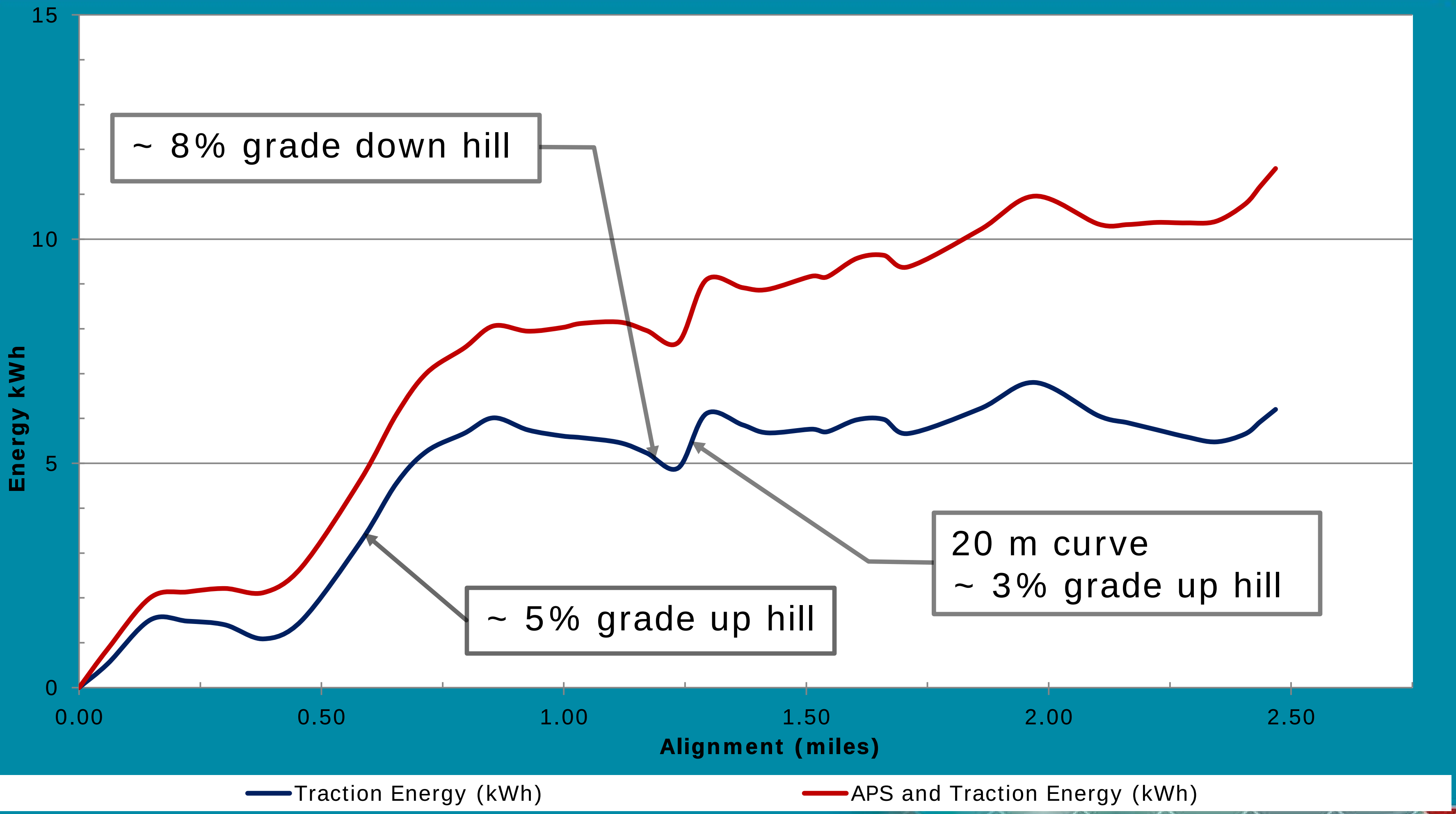
Study Methodology

- Developed alignment energy profiles as a function of performance parameters
  - Acceleration rate
  - Auxiliary power load (HVAC)
- Combined the intersection analysis with the energy profiles identifying favorable areas for wireless operation

Example Energy Profile
AW2 Vehicle, Round Trip



Example Wireless Profile
AW2 Vehicle, Inbound



~ 8% grade down hill

~ 5% grade up hill

20 m curve
~ 3% grade up hill

Conclusions

- Wireless operation is an emerging technology, being tried in several places
- Performance requirements significantly affect feasibility of wireless operation
  - Alignment profile
  - Duty cycle
    - Charging and discharging OESS
    - Acceleration rate
  - OESS technology
  - OESS life
- Operation should be from Station-to-Station
- OESS voltage at least 500 Vdc

Conclusions

- First Hill Streetcar alignment appears feasible for wireless operation
- Desirable wireless regions
  - Outbound
    - Pioneer Square Terminus to Jackson and 5th
    - Broadway and Pine to the Capitol Hill Terminus
  - Inbound
    - Jackson and 7th to the Pioneer Square Terminus
- Possible wireless region
  - Complete Inbound route
    - Large up hill grade in beginning of region

Procurement Process

Vehicle Procurement Approach

- 6 cars
- Two step best value—RFP and RBAFO
- Quantitative assessment
- Technical 60%
  - Vehicle description
  - OESS
  - Management approach
  - Schedule
  - Qualifications
  - Buy America capability

Price 40%

6 Vehicles

System support

Spare parts

Option vehicles

Option services

Vehicle Procurement Schedule

Issue RLOI	June 2010
Issue RFP	March 2011
Receive proposals	June 2011
Evaluate/rank proposals	June 2011
Meet with Proposers	July 2011
Issue Request for BAFO	August 2011
Receive BAFOs	October 2011
Evaluate/rank BAFOs	October 2011
Issue Notice of Intent to Award	October 2011
Issue NTP	March 2012

RFP
Reevaluating Wireless Operation

- The first step (RFP) produced proposals in excess of the vehicle procurement budget

- Key Factors
  - Cost of the Onboard Energy Storage System
  - Excessive wear on equipment due to having 3 wireless regions
    - 2 Outbound
    - 1 Inbound

RBAFO

- Added alternate extended wireless region
  - Inbound line completely wireless

- Permitted two separate BAFOs
  - Conventional car
  - OESS car

- Evaluation involved selecting
  - Best value Conventional
  - Best value OESS
  - Determining the best value overall

BAFO Results

OESS	Conventional
Inekon Group	Inekon Group
KinkiSharyo	Oregon Iron Works
Oregon Iron Works	

- Contract awarded to Inekon Group (IG) of Czech Republic
  - $26.7M
  - 6 OESS cars
  - System support, spare parts, etc.

Wireless Requirements

- Wireless segment is entire inbound route
  - 2.5 miles
  - Predominately downhill

- Performance requirements are reduced
  - Acceleration rate 1.34 m/s^2 (AW2)
    - Rate rolls off at 12 km/h
  - Maximum speed at least 32 km/h
  - HVAC, ventilation only
    - Currently, looking into adding AC and heating

Wireless Requirements

- Recharging occurs
  - Pantograph is connected to the OCS
  - OESS mode, during regenerative braking

- OESS safety
  - OESS is interlocked with the pantograph
  - Pantograph status, up/down, is communicated to the wayside
  - NFPA-130 requirements
  - OSHA requirements

Vehicle Description

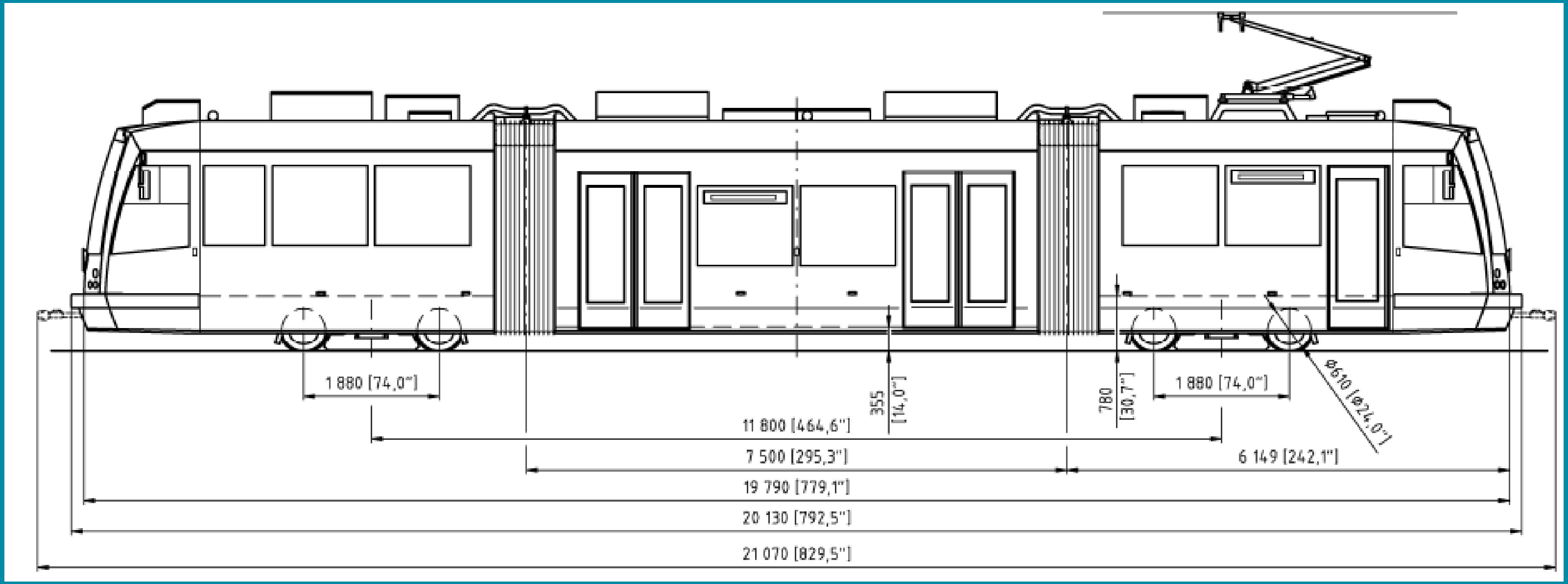
IG Vehicle Overview

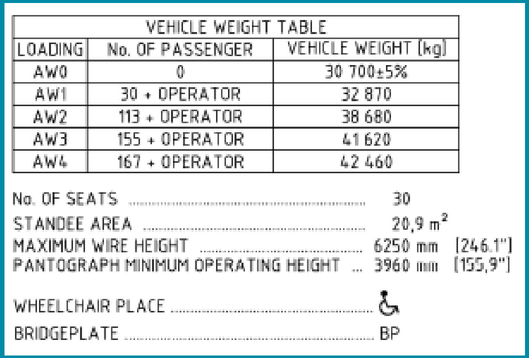
- Based on existing SLU design
- 50% low floor, three car sections, two trucks
- 66 ft in length
- 30 seats
- Welded steel construction, bonded stainless steel side cladding, FRP front end
- 69,000 lbs AWO estimated
- Liquid cooled, microprocessor-controlled AC inverter
- Onboard energy storage system (OESS)
- Hydraulic brakes
- Coil spring secondary suspension
- Bridgeplates, for ADA accessibility

Major Suppliers

Carbody	Inekon (Ostrava)
Truck frames	
Final assembly first car	Inekon (Ostrava)
Final assembly cars 2-7	Pacifica (Seattle)
Propulsion	ABB
OESS	ABB/SAFT
Network	ABB/Selectron
Friction brakes	Knorr
Doors	Bode
HVAC	Meran

General Arrangement



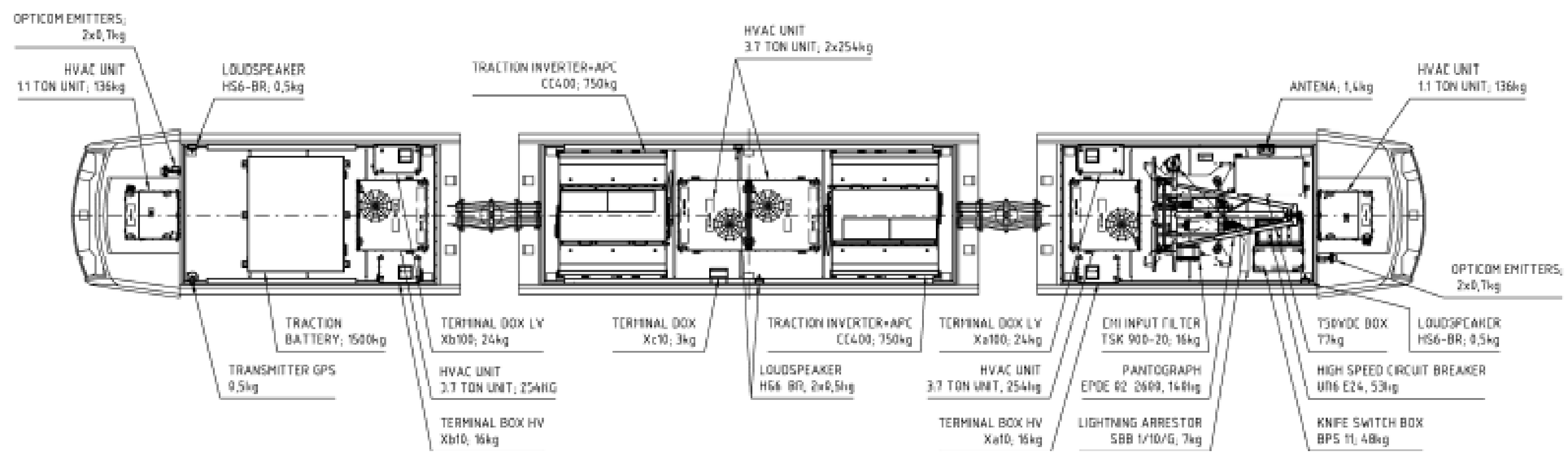


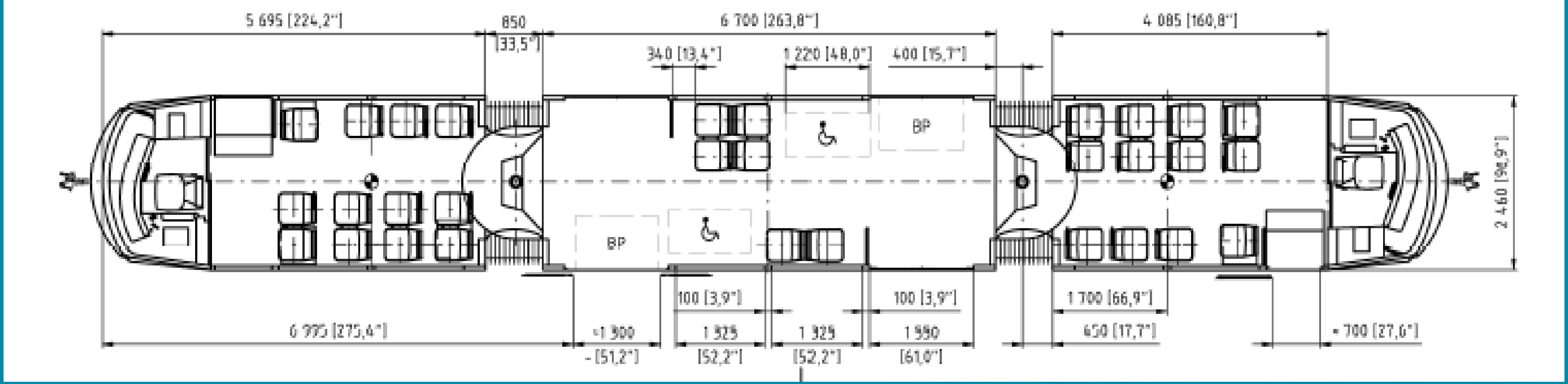
VEHICLE WEIGHT TABLE

LOADING	No. OF PASSENGER	VEHICLE WEIGHT [kg]
AW0	0	30 700±5%
AW1	30 + OPERATOR	32 870
AW2	113 + OPERATOR	38 680
AW3	155 + OPERATOR	41 620
AW4	167 + OPERATOR	42 460

No. OF SEATS	30
STANDEE AREA	20,9 m²
MAXIMUM WIRE HEIGHT	6250 mm [246.1"]
PANTOGRAPH MINIMUM OPERATING HEIGHT	3960 mm [155,9"]
WHEELCHAIR PLACE	♿
BRIDGEPLATE	BP

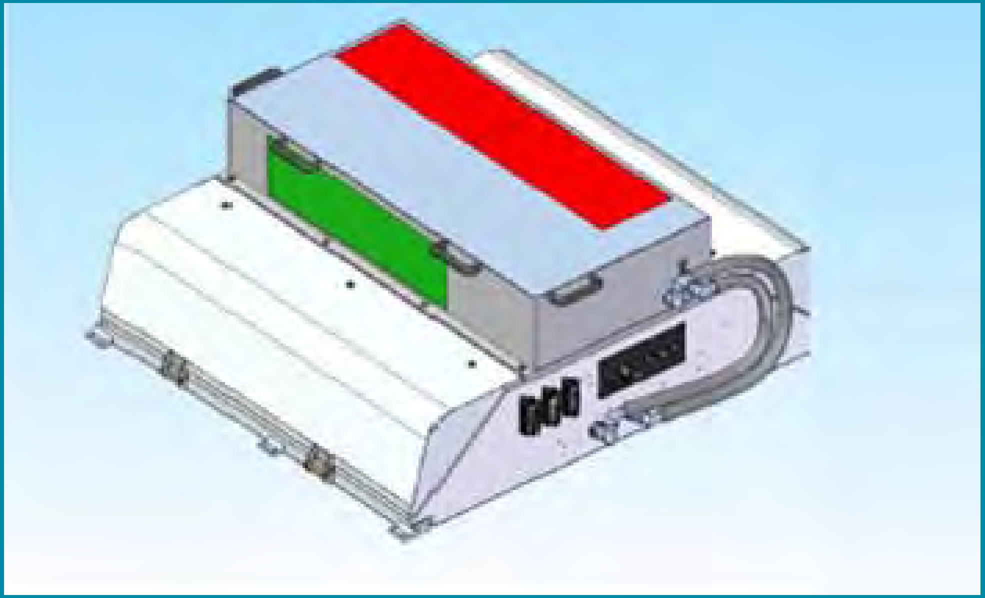
General Arrangement


OPTICOM EMITTERS; 2x0,1kg
HVAC UNIT 1.1 TON UNIT; 136kg
LOUDSPEAKER HS6-BR; 0,5kg
TRACTION INVERTER+APC CC400; 750kg
HVAC UNIT 3.7 TON UNIT; 2x254kg
ANTENA; 1,4kg
HVAC UNIT 1.1 TON UNIT; 136kg
OPTICOM EMITTERS; 2x0,1kg
TRACTION BATTERY; 1500kg
TRANSMITTER GPS 0,5kg
TERMINAL BOX LV Xb100; 24kg
HVAC UNIT 3.7 TON UNIT; 254KG
TERMINAL BOX HV Xb10; 16kg
TERMINAL BOX Xc10; 3kg
TRACTION INVERTER+APC CC400; 750kg
LOUDSPEAKER HS6-BR; 2x0,5kg
TERMINAL BOX LV Xa100; 24kg
HVAC UNIT 3.7 TON UNIT; 254kg
TERMINAL BOX HV Xa10; 16kg
EMI INPUT FILTER TSK 900-20; 16kg
PANTOGRAPH EPDE 02 2609; 148kg
LIGHTNING ARRESTOR SBB 1/10/G; 7kg
750VDC BOX 77kg
LOUDSPEAKER HS6-BR; 0,5kg
HIGH SPEED CIRCUIT BREAKER UR6 E24; 53kg
KNIFE SWITCH BOX BPS 11; 48kg



Unitized Propulsion Inverter

- 2 Traction inverters
- OESS charger
  - Integrated into Traction Inverter
- 1 Auxiliary converter
- 1 LVPS
  - Battery charger
- Braking resistors
- Liquid cooled
  - Traction inverter
  - Auxiliary converter
  - LVPS



Schedule

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Schedule Highlights

NTP	March 2012
Start carshells	November 2012
Start final assembly car 1	March 2013
Compression test car 2	February 2013
Combined propulsion/OESS test	February 2013
Ship carshell 2 to Pacifica	April 2013
Ship car 1 to SDOT	December 2013
Ship car 2 to SDOT	February 2014
Ship cars 3-7 to SDOT	March to June 2014

The New Seattle Streetcar With Onboard Energy Storage

Ethan Melone

Seattle Department of Transportation

Streetcar Project Manager, Seattle WA

Denny Porter / Jason Krause

LTK Engineering Services, Consultants, Portland OR

FLYWHEEL PUTS RAIL INTO RACING MODE

FORMULA ONE TECHNOLOGY IS OFFERING TRAINS A BOOST. AN ELECTROMECHANICAL, COMPOSITE FLYWHEEL, DEVELOPED BY WILLIAMS HYBRID POWER (WHP), PROMISES FLEETS A HIGH-POWER, COST-EFFECTIVE, AND ENVIRONMENTALLY FRIENDLY SOLUTION FOR MOBILE OR STATIONARY ENERGY RECOVERY AND STORAGE.

The company's first application of the technology was in the tough environment of Formula One racing. Through development of a flywheel for Williams F1's Kinetic Energy Recovery System (KERS), WHP is confident it has proved its engineering capabilities in the composite flywheel field, as well as improving aspects of the technology in the process.

Building on the racing project, WHP is now making the technology available to meet high-power energy storage needs in a variety of applications, which include hybrid passenger vehicles and buses, rapid transit systems, light rail, and electric trains. "From a power-density point of view, the flywheel is better than the battery; from an energy density view, batteries are better than the flywheel," says Ian Foley, managing director, WHP. "The flywheel technology is ideal for vehicles with regular starts and stops," he adds. "Because although the energy storage period is shorter, buses and trains typically use energy within a shorter period of time, plus it is released more quickly."

The flywheel serves as a reservoir for storing the energy recovered by the KERS in mechanical form. With an electrical, rather than a mechanical connection to the motor, it delivers a higher energy yield of around 95%, compared to 60%, due to fewer losses. For electrically connected flywheels, this loss typically occurs in the electronics, e.g. the windings; for the mechanical, via friction and in the gearboxes. Meanwhile the 100% composite (carbon and glass fibre) rotor delivers various benefits, which include the ability to be continuously deep-cycled at high power with no impact on performance or a reduction in life cycle, as well as improved safety: in the event of a failure, there are no metallic fragments requiring containment.

TESTING TIME

Two of the flywheel storage systems have already been put to the rail test at Bombardier's 1.88km test track in Kingston, Ontario (Canada). Characteristics of the units studied over four weeks in 2011 included energy savings, emergency reserve, and voltage support. The single car test train was pro-

This year's 80th edition of the *24 Heures du Mans* sports race in France was won by the Audi R18 e-Tron Quattro, with a supporting role by WHP's electric flywheel technology. In the process, the car also made history as the first hybrid-powered vehicle to finish on the podium.

Williams Hybrid Power designed an entirely new, ultra-lightweight electric flywheel and associated power electronics to ensure its solution outpaced other potential technologies such as batteries, ultra-capacitors, or mechanical flywheels when fitting the car. "Our flywheel technology started its life as a motorsport application," commented Ian Foley, managing director of WHP, "and whilst it's since been adapted for a variety of other purposes, motorsport will always be close to our heart, and is the ultimate proving ground for our technology."

pelled and braked using a single (instead of two) Linear Induction Motor. The positive results released include the following:

- the flywheels were able to capture, store, and regenerate 100% of the available braking energy, resulting in energy savings of between 2 to 16%. And this despite limiting factors such as the mass of the single car train, the single LIM, train windage and rolling losses, and the lack of train regenerating power at speeds below 20km/hr
- furthermore, they powered the train at 60km/hr for 1,364 metres using stored flywheel energy only. And the track voltage increased by over 10Vdc during acceleration of the train, thanks to the flywheels supplying up to 75% of the required current.

IN THE WIDER FIELD

For markets like India, China, and the Middle East, Williams sees the flywheel as an integral part of new and 'smarter' rolling stock. While for other markets with fleets already in service, retrofitting the technology is the solution. "When making the case for the flywheel, you really have to consider the major benefits of energy savings over the years," insists Doug MacLennan, sales & marketing manager, Williams Technology Centre, Qatar. And a further benefit of the retrofit to bear in mind, he told EURAILmag, is the potential savings to be made when it comes to investment in infrastructure: "Since more and more rolling stock is being upgraded, if the electrical infrastructure is not also upgraded to stay in line, the system-level voltage is not maintained. But with the flywheel technology, it is."

Aware of the costs involved for manufacturers when introducing new technology, which leads to more expensive end products, "push-pull" is how Mr MacLennan describes the current market situation. "We are seeing pull, i.e. demand, from end users saying 'we want this,' while the push needs to come from Original Equipment Manufacturers such as ABB in Switzerland and Schneider Electrics in France, together with constructors like Bombardier, Alstom, and Siemens■"

Lesley Brown

All photos ©Williams Hybrid Power

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Hall 10.1, Stand 213

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Thursday, January 17, 2013

New technology planned for Alstom Citadis LRVs

Written by Douglas John Bowen

1

Alstom Transport/R. Vilalta

Alstom and Williams Hybrid Power Thursday announced they have signed an agreement to apply Williams Hybrid Power's energy storage technology to Alstom's Citadis light rail transit (LRT) vehicles by 2014.

The two companies companies will "work together to adapt and develop an energy storage solution that has the potential to reduce the greenhouse gas emissions of Alstom's rolling stock."

Originally developed for the 2009 Williams Formula One car, Williams Hybrid Power's energy storage technology has since been introduced into applications such as London buses. The companies say the technology offers fuel savings and emissions reductions by harvesting the energy that is normally lost as heat when braking and turning it into additional power. "It is ideally suited to trams [LRT vehicles] because of their stop-start nature and high mass. Furthermore, the flywheel's rotor is made of composite material which is inherently safe because there is no metallic structure travelling at very high speed," the two companies said.

"As a world leader in rail transport technology, Alstom is continuously looking to challenge and improve the energy efficiency of its trains," said Alstom Transport Innovation Director Dominique Jamet. "We are proud to announce the collaborative project with Williams Hybrid Power that aims to deliver an innovative solution that does not only save energy but also re-use it to add more power to the tram while reducing energy use and CO2 emissions."

Ian Foley, Managing Director of Williams Hybrid Power Managing Director Ian Foley said, "From the very beginning we highlighted trams as an ideal application for our technology and to be collaborating with the market leader on this project is very exciting. We both share a common goal – developing the next generation of green transport technologies – and this agreement will hopefully prove pivotal in finding a solution that not only cuts carbon emissions but crucially cuts costs for the end user.'

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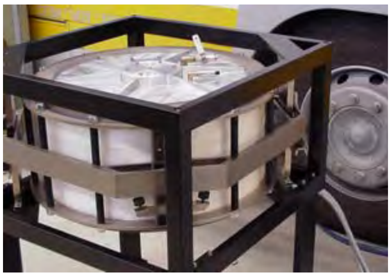
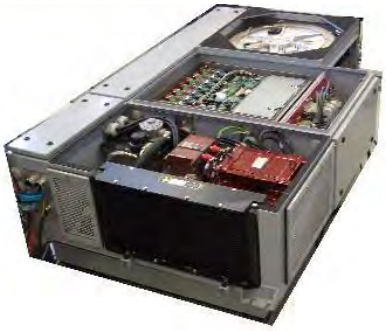
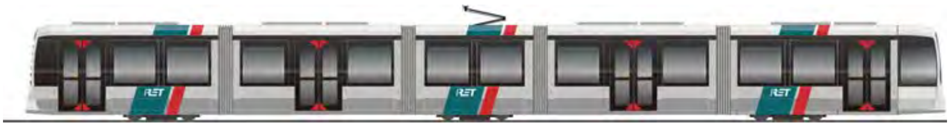
Citadis Rotterdam as Flywheel Demonstrator







CITADIS with flywheel:

The CITADIS is a modern, fully low floor tram of Alstom. For test & demonstration a CCM flywheel system has been installed on CITADIS roof. The CCM flywheel offers CITADIS capabilities as: “Autonomy Mode” (wireless tram) and “Economy Mode” (energy recovery and less heavily loading of energy supply infrastructure).

Results of tests:

- The vehicle can be operated as a normal CITADIS
- In “Autonomy Mode” the vehicle (40 tons) has shown the following results:
    - 2,000 m running distance without overhead wire
    - the vehicle can run up to 50 km/h on flywheel power
    - the Erasmus bridge (Length 900 m; Height 15m) in Rotterdam is crossed in “Autonomous Mode”
    - covering 3 stops before re-charging is required
- The “Economy Mode” is under test now. The flywheel system will recover brake energy and less heavily load the energy supply infrastructure

Centre for Concepts in Mechatronics
P.O. box 12
5670 AA Nuenen
The Netherlands
tel: +31(0)40 263 5000
frans.thoolen@ccm.nl

Nuenen,
February 2005

Flywheels as High Power Storage Devices for Mobile Applications

YOUR
PRODUCT
INNOVATION
PARTNER
technology for business

IRES-I Conference
Gelsenkirchen, 30-31 Oct. 2006
Dr. Frans Thoolen

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Applications

Peak Power Shaving

- *Mobile*
  - *Road*
  - *Rail*
  - *Marine*
- *Stationary*
  - *UPS*
  - *Track side*
  - *Renewables*
- *Others*
  - *Lifting/ Hoisting*

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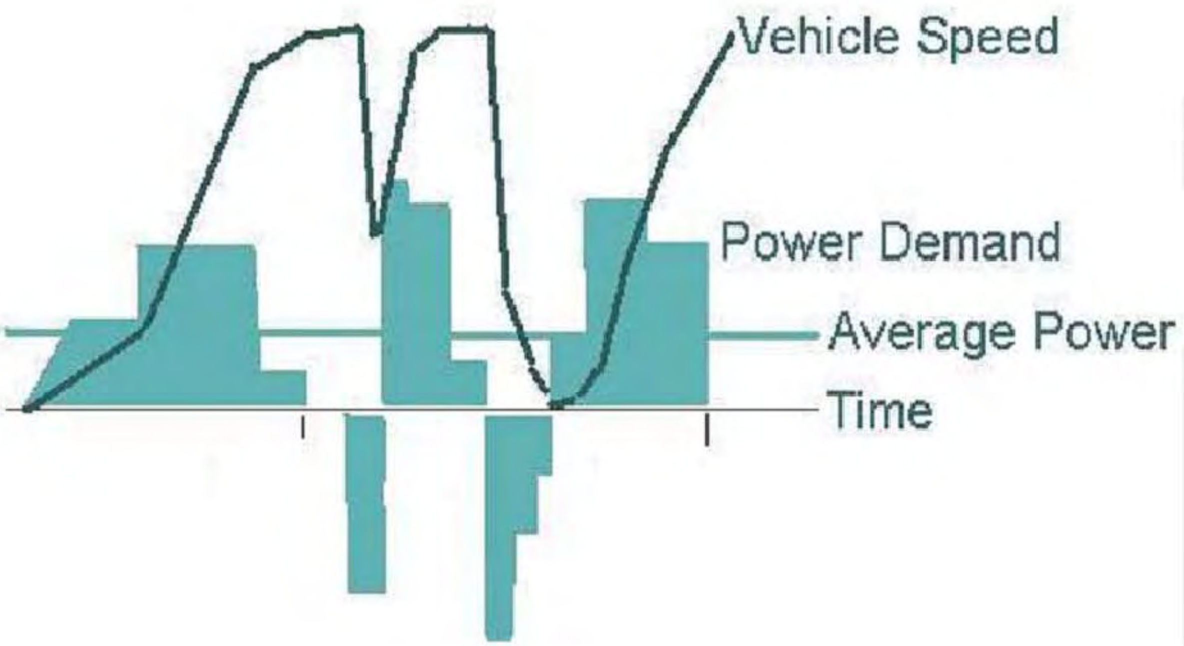
Peak Power Shaving

Typical urban drive cycle



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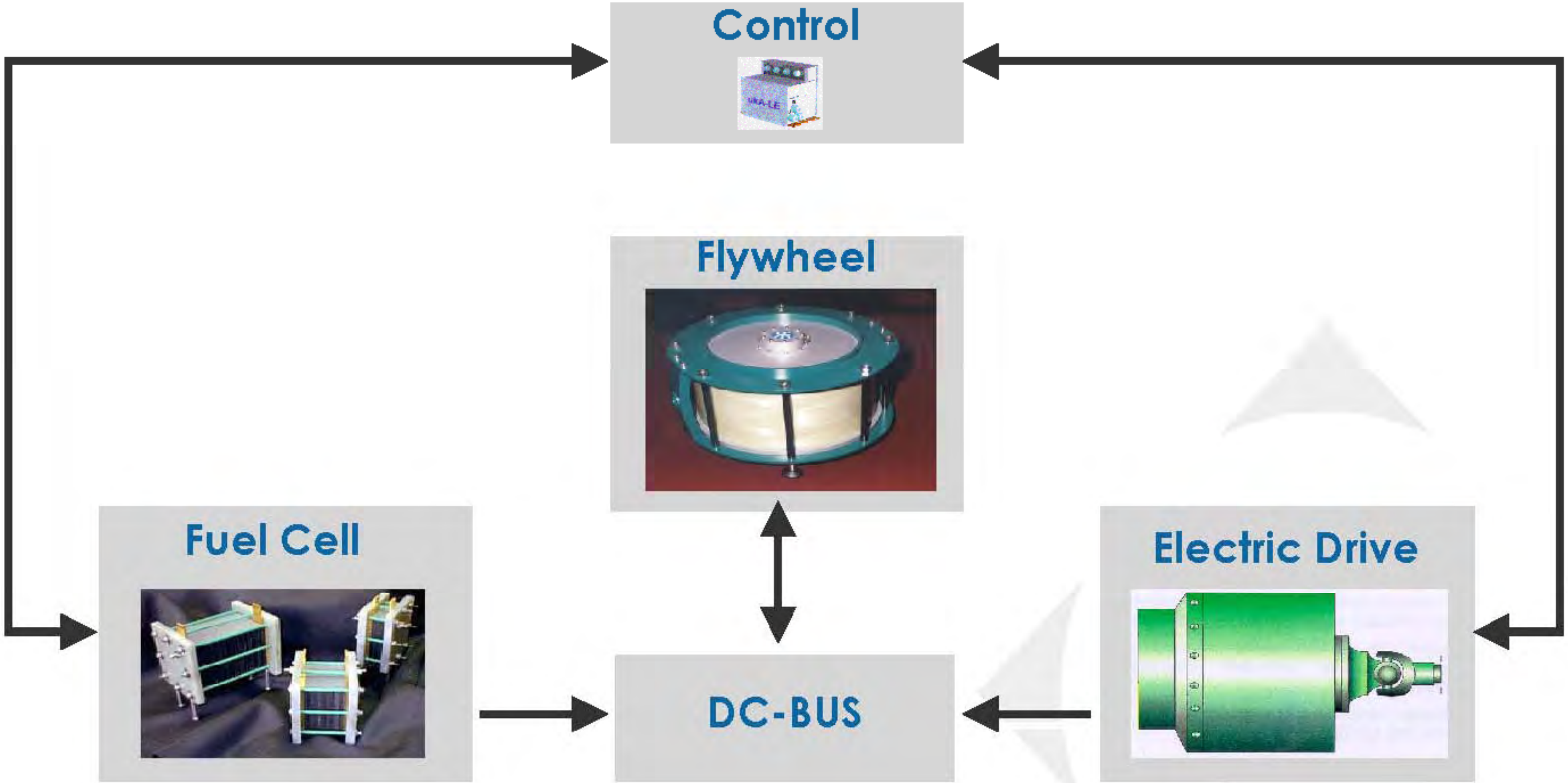
Modular Drive System



Control

Flywheel

Fuel Cell

DC-BUS

Electric Drive

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Storage Technologies

	Power	Energy	Cycle life	Chemi-cals	Typical Load cycle times
Super Capacitor	++	-	+	*Yes*	*Seconds*
Battery	-	++	-	*Yes*	*Minutes to hours*
Flywheel	+	+	++	*No*	*Seconds to minutes*

Different load requirements call for different storage technologies

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Flywheel Energy Density

Energy storage
$E=\frac{1}{2}.J.\ \Omega^{2}$

Power
$P = T\ .\ \Omega$

	Steel flywheel	Carbon flywheel
J (inertia)	*1*	*1/3*
Ω (rotation speed)	*1*	*4*
E (energy storage)	*1*	***>5***

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Flywheel safety

Passive Safety

- ***Fail-safe rotor***
- ***Ceramic bearings***
- ***Robust containment***
- ***Collision-proof frame***

Active Safety

Guarding :

- ***temperature***
- ***speed***
- ***vibrations***
- ***current***

Automatic shut-down above alarm levels

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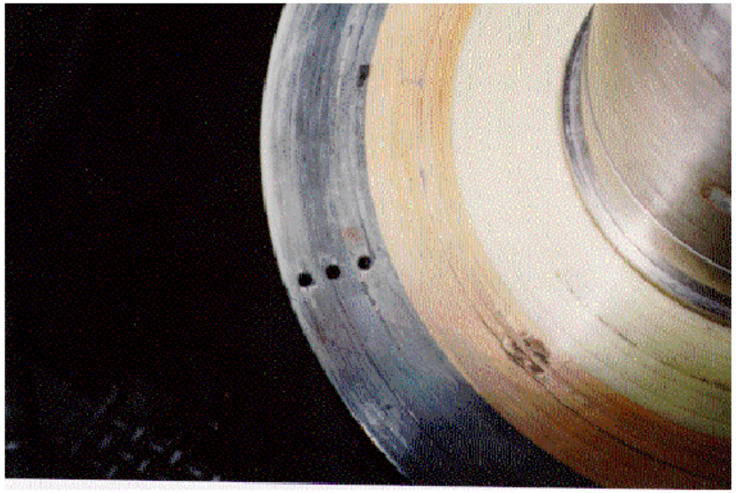
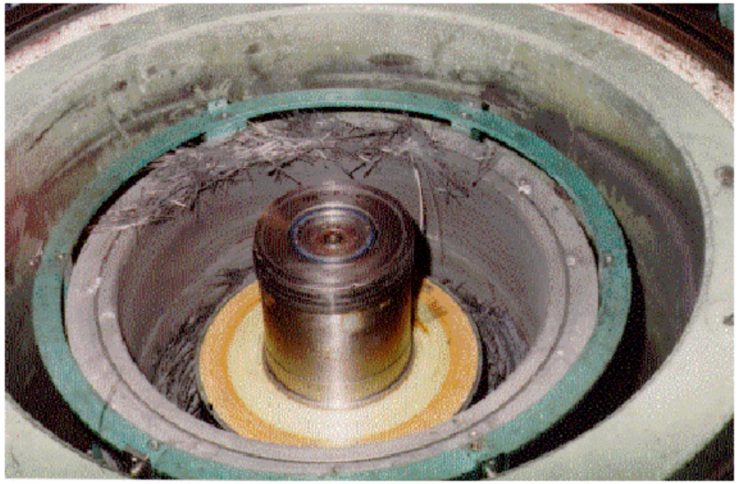
Flywheel safety tests



Rotor failure

Containment qualification



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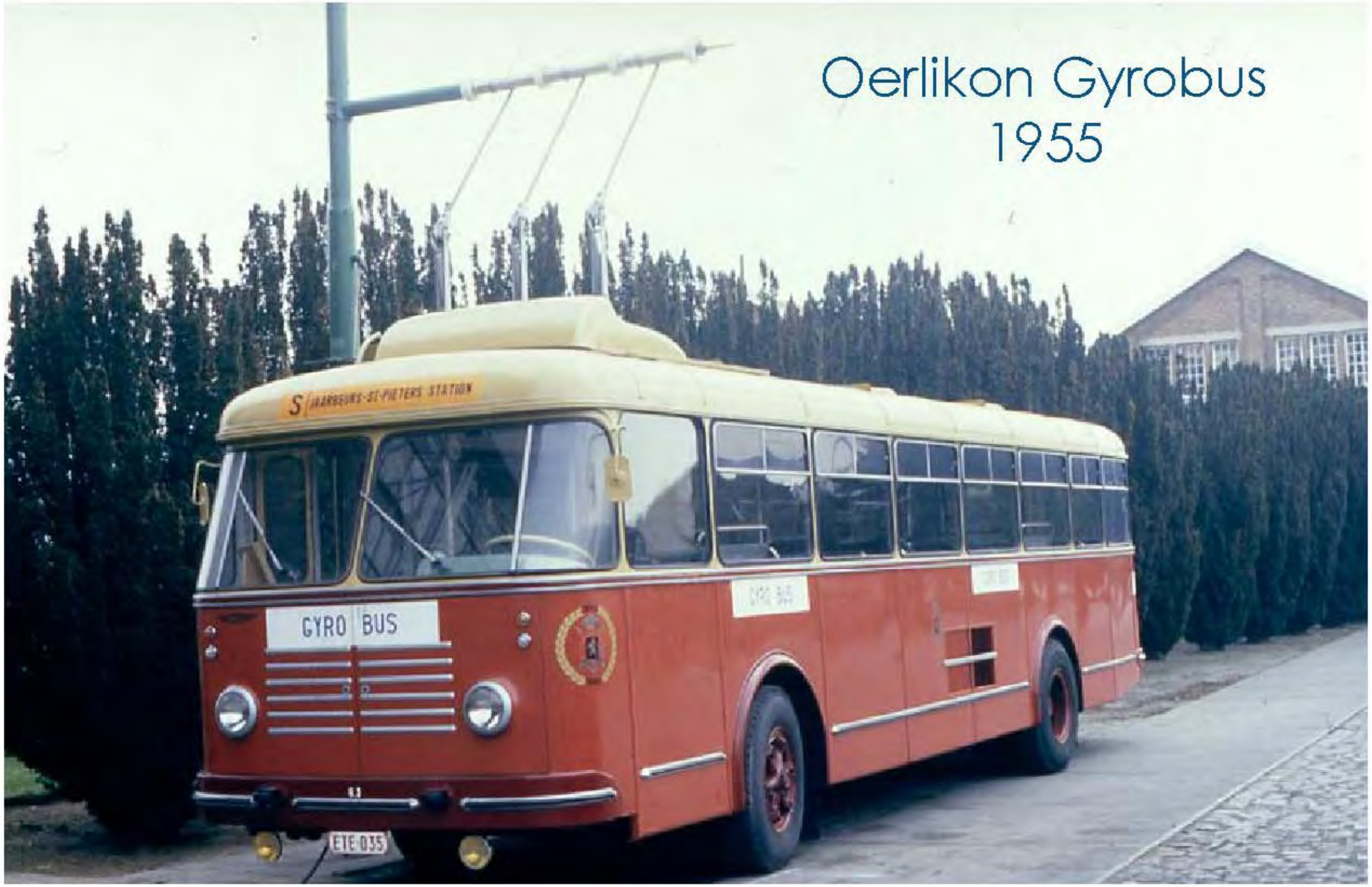
Flywheel history



Oerlikon Gyrobus
1955

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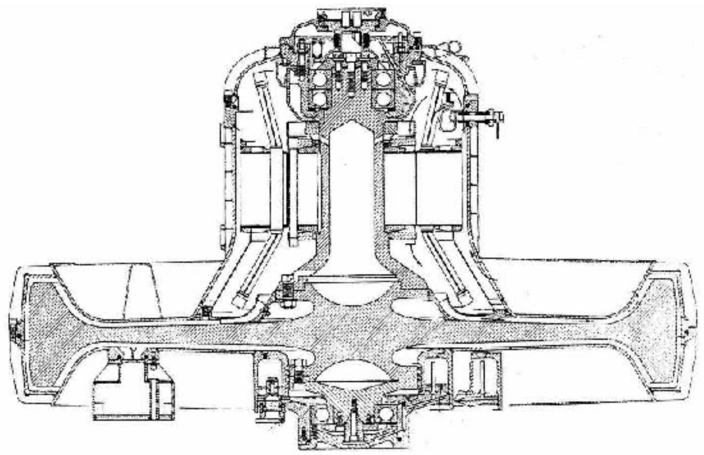
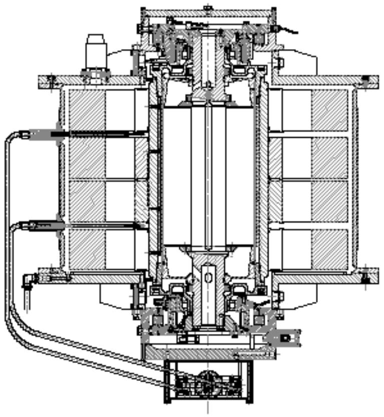
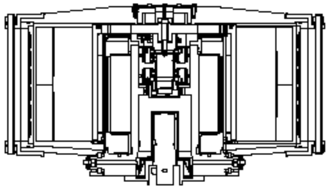
Flywheel miniaturization

1955 Oerlikon → 1995 CCM → 2004 CCM







1955 Oerlikon	1995 CCM	2004 CCM
3.13 kWh / 130 kW	4 kWh / 300 kW	4 kWh / 300 kW
3,000 rpm	15,000 rpm	22,000 rpm
Ø1700 x 1100 mm	Ø900 x 900 mm	Ø780 x 450 mm
3000 kg	850 kg	375 kg

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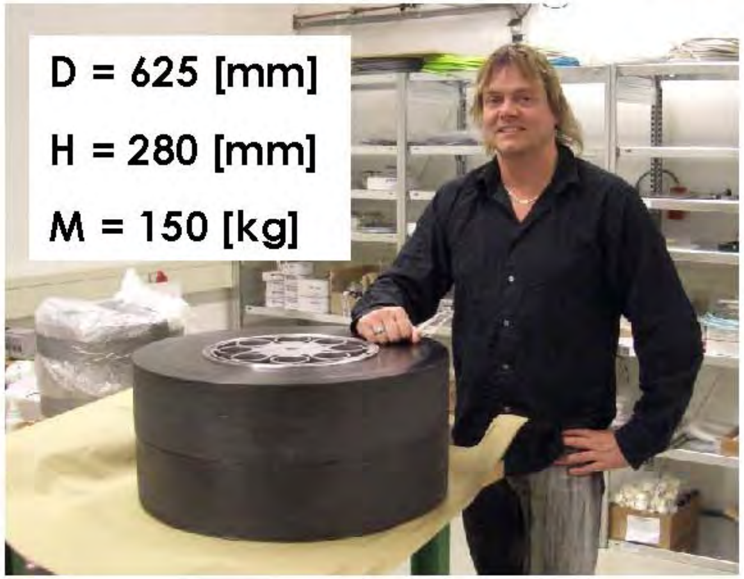
Modular Concept

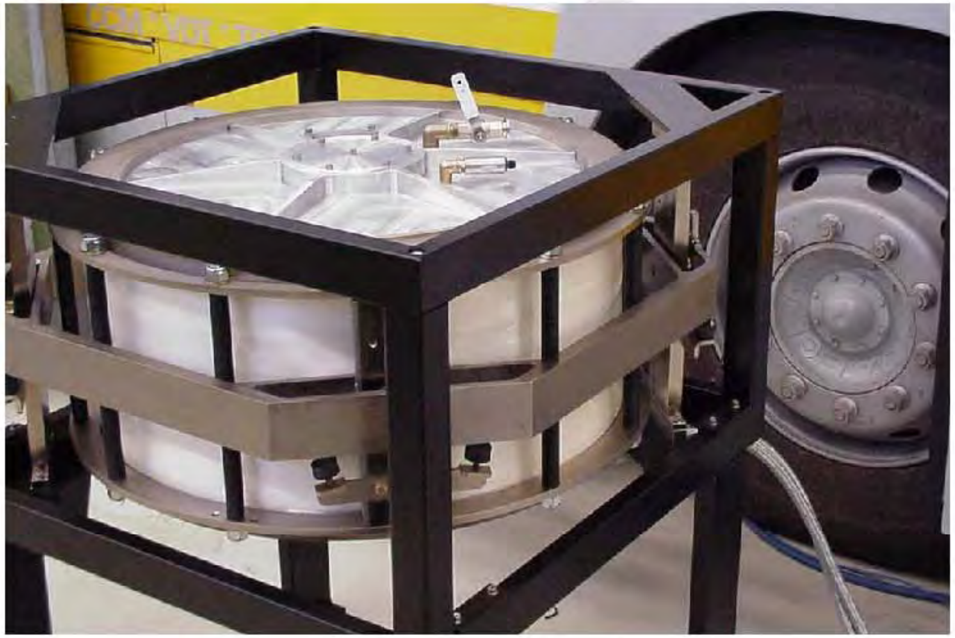
- Fully integrated high power Permanent Magnet Motor/Generator
- High speed carbon fiber flywheel
- Compact bearing module
- Vacuum/safety containment



D = 625 [mm]

H = 280 [mm]

M = 150 [kg]



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Product Portfolio Mobile

Type	Application	Status
RxV- 0 FMG*: Ø300x225[mm];28[kg] 50kW during 25 sec **About 0.33 kWh effective**	Passenger Cars (<1.5 tons)	Future Development
RxV- I FMG*: Ø600x450[mm];225[kg] 150kW during 50 sec **About 2 kWh effective**	Light-weight vehicles (<15 tons)	Under progress
RxV- II FMG*: Ø780x450[mm];375[kg] 300kW during 50 sec **About 4 kWh effective**	Medium-weight vehicles (15~30 tons)	Dedicated Project applications
RxV- III FMG*: Ø950x650[mm];875[kg] 750kW during 50 sec **About 10 kWh effective**	Heavy-weight vehicles (>30 tons)	Future Development

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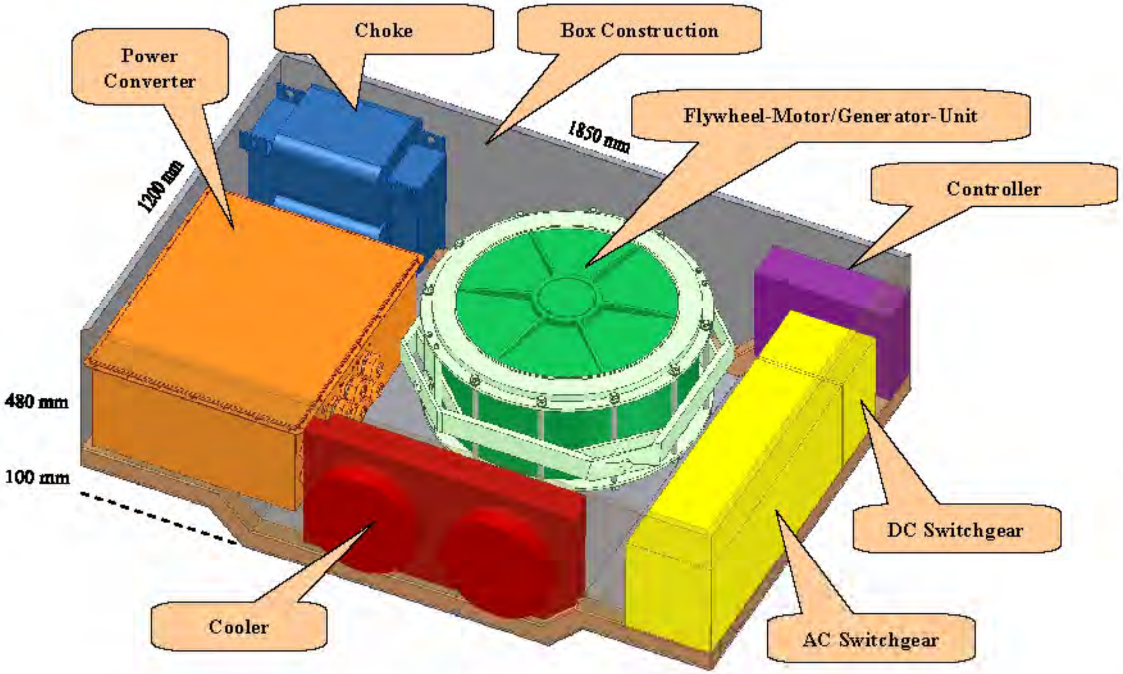
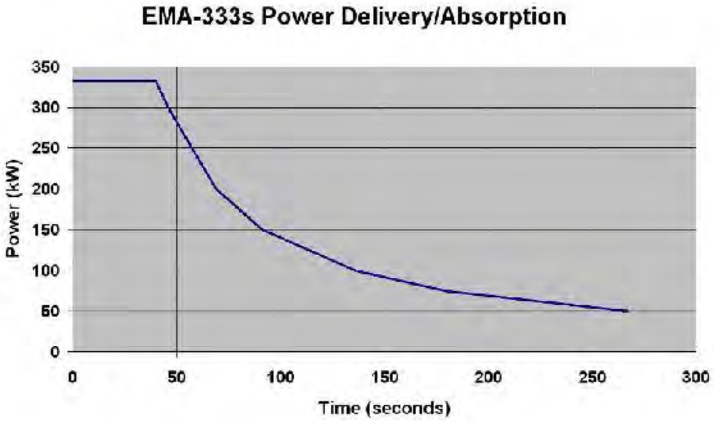
EMAFER RxV-II Data

Layout Example



L x W x H = 1100 x 2000 x 550 mm

Mass = 1100 kg



Power (kW)	Time (s)
333	40
300	46
200	69
150	91
100	136
75	180
50	267

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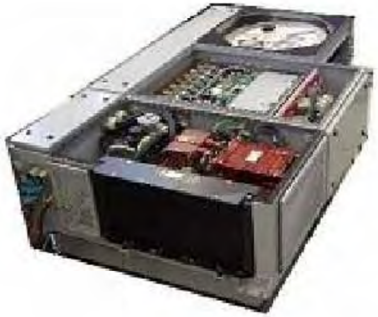
Recent Projects

Citadis with flywheel installed on the roof



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Recent Projects

Fraunhofer AutoTram

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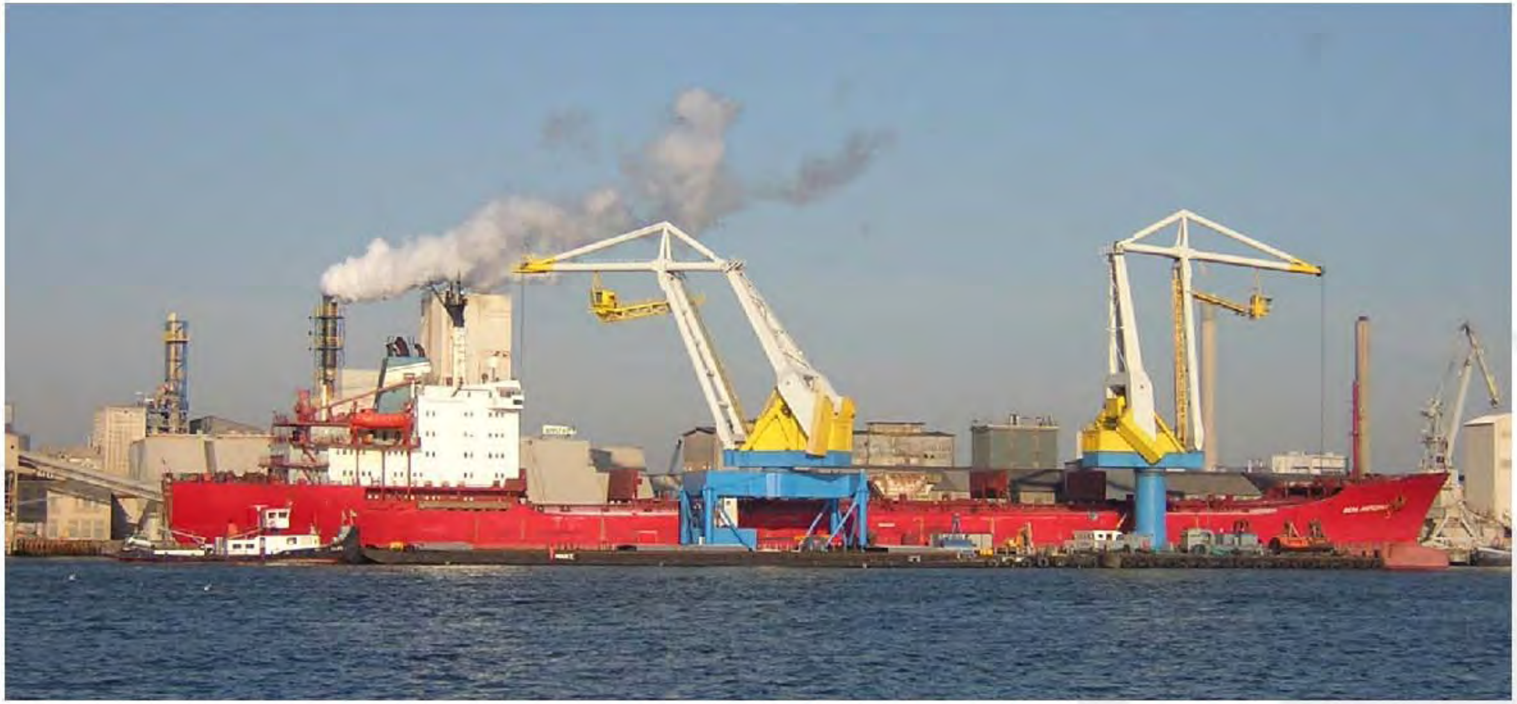
Recent Projects

Maja Stuwadoors: Floating Grab Crane



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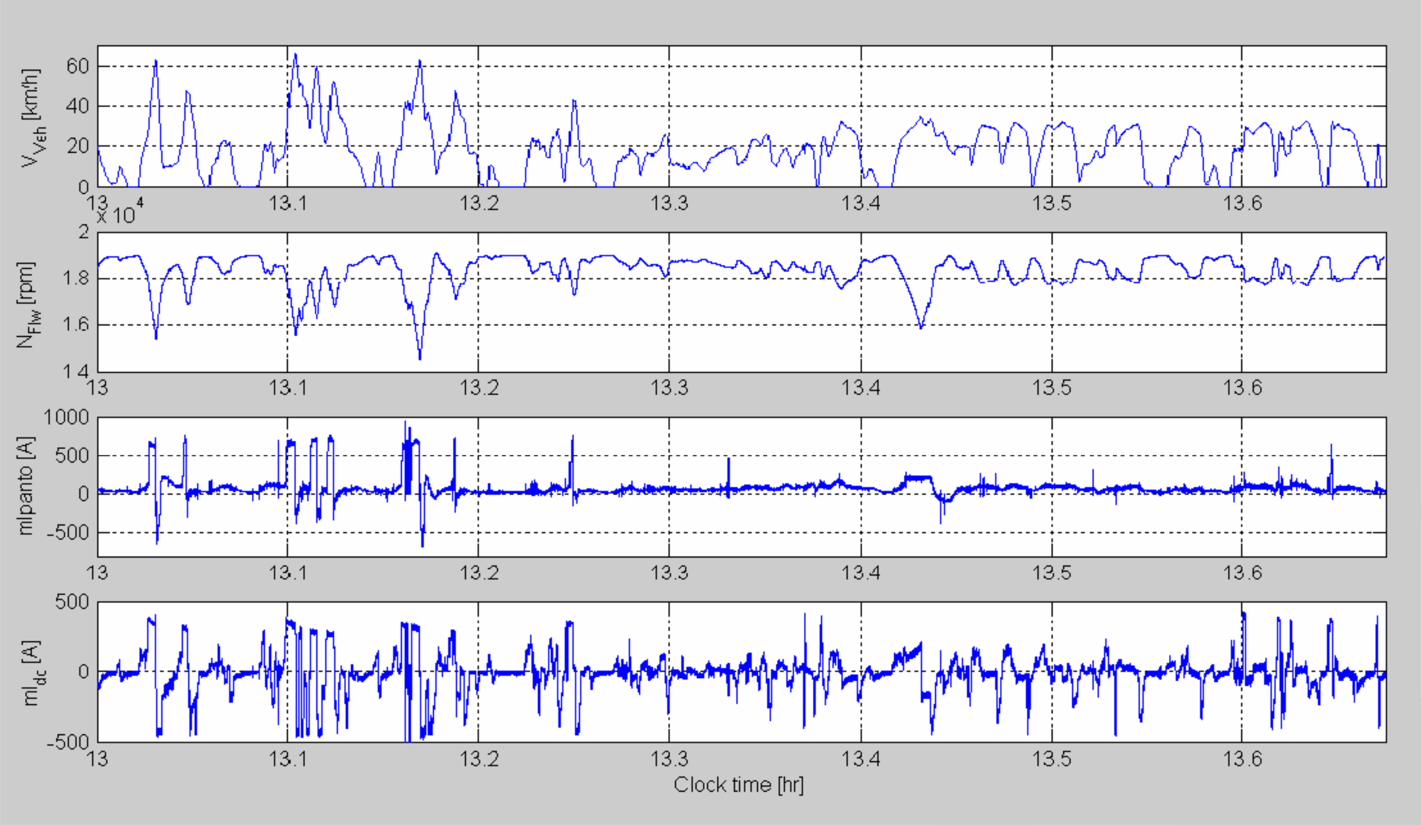
Results: Flywheel tram Eco-mode



$I_{driveRMS}$=243 A ; $I_{pantoRMS}$=198 A

→ 39.2% reduction in line current

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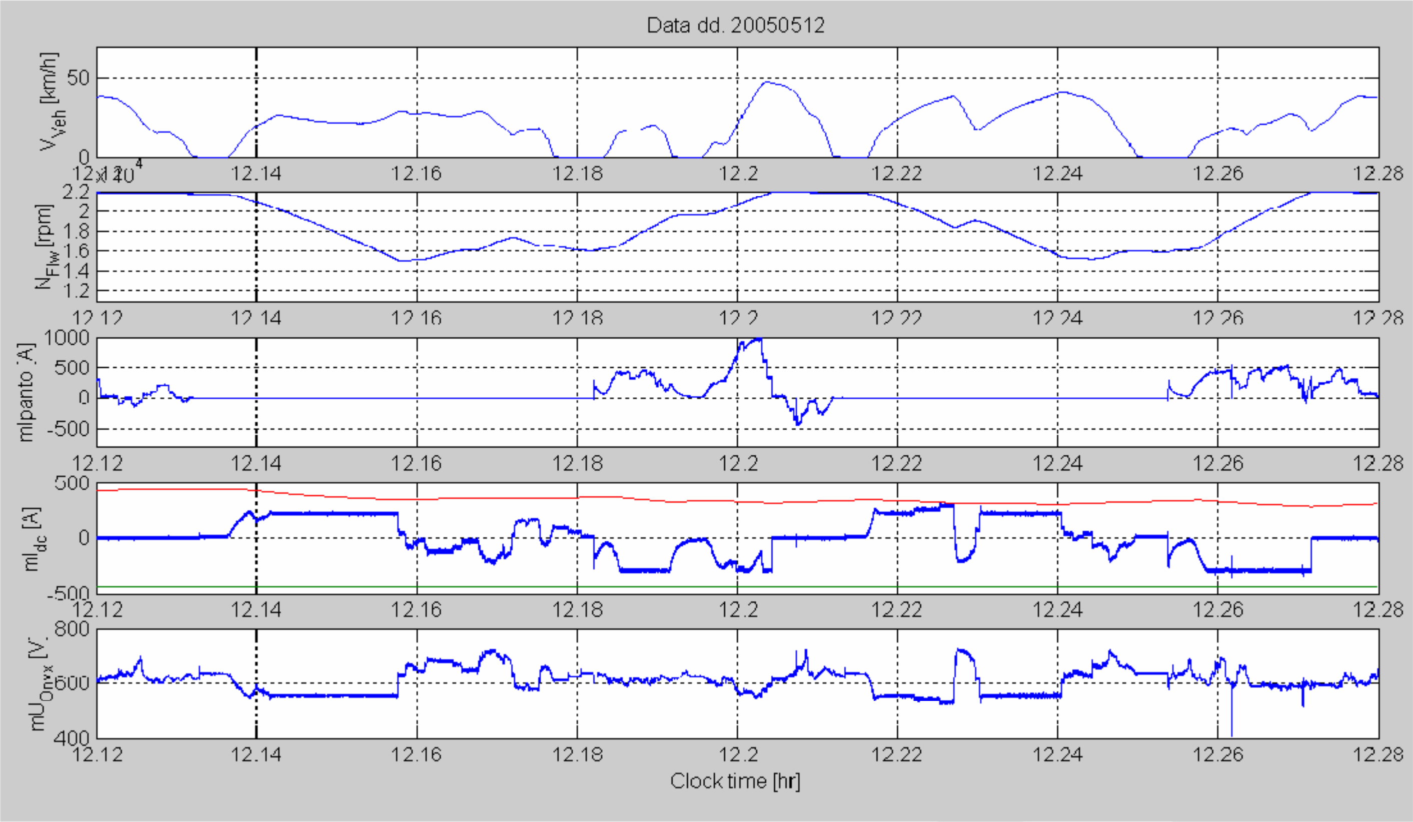
Results: Flywheel tram Autonomous-mode



Crossing the Erasmus bridge:

Several minutes ride without overhead

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De Pinckart 24
P.O. Box 12
5670 AA Nuenen
The Netherlands

Phone +31(0)40-2635000
Fax +31(0)40-2635555

E-mail info@ccm.nl
Web www.ccm.nl

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Thank you for your attention

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Kassel diesel-hybrid tram on Zierenberg viaduct (Kassel – Wolfhagen route). Diesel operation avoids the need to provide visually-intrusive overhead line equipment. Compare this with the listed viaduct at Chappel & Wakes Colne which would prevent electrification on the Sudbury branch. *Heribert Menzel*

Diesel trams: a new way forward?

Charles King suggests a novel approach for secondary routes

Light rail technologies have received closer attention in recent times as potential solutions to transport problems as well as providing alternatives to 'traditional' railway operation. In light of this, a trip run by ACoRP (Association of Community Rail Partnerships), and organised by Faber Maunsell, took eight delegates from Network Rail, the Department for Transport and Transport Scotland in December last year to Switzerland and Germany. The aim of this was to study developments in light rail and their applicability to the UK.

A major focus of this trip was 'tram-train'. For many people, this concept is most closely associated with the city of Karlsruhe in south-west Germany, which pioneered the technology in the 1990s. Essentially it involves the 'joining-up' of a tram network with heavy rail so that local services sharing paths with conventional trains on the main line can travel over both systems, enabling seamless through journeys. The need to change modes is thereby eliminated: accessibility is improved and end-to-end journey times drop. In Karlsruhe's case, the city centre, about two km from the main station, was the main attraction, and a through journey from the suburbs with dual-voltage electric trams was made possible.

Factors for success

Karlsruhe's success has led to numerous developments and extensions, most recently conversion of the 30-km long Murgtalbahn to tram-train operation, which took only seven years from conception to completion at a cost of Euro75million (£50million). The longest possible journey on the system now takes in tramways in both Karlsruhe and Heilbronn as well as main-line railway over its 150-km route from Achern to Öhringen.

But it is perhaps surprising that not more schemes modelled on this apparently thriving example have come to fruition, even in continental Europe. Those that are operational include Saarbrücken in Germany and the Rijn-Gouwe-Lijn through Leiden and Gouda in the Netherlands, with the French city of Mulhouse at the initial stages. An overview of these projects reveals that a certain number of factors typically have to come together for a scheme to work:

- a common tram and heavy rail track gauge and a suitable interface point between heavy rail and tramway;
- a relatively large but dispersed population, ideally with a strong commuting market – Karlsruhe, for instance, serves 120 communities with a total population of 1.3million people;
- favourable urban planning and public transport characteristics – the two must be considered together;
- existing heavy rail stations some distance from the main centres they seek to serve;
- an ability to overcome the technological challenges such as providing trams with two sorts of traction equipment, signalling compatibility, and meeting the relevant safety standards;
- perhaps most importantly, the political will and funding to see the project through.

Latest developments

One city where the balance of factors has been positive, however, is the city of Kassel in central Germany, which is currently developing its own 'RegioTram' system, due to open in June this year. A total network of 122km is provided with only 10km of new track, serving an urban population of 220,000 with a further 400,000 in the surrounding area. Although the system is based on the 'classic' tram-train principle with dual-voltage trams running on the mainline at 15kV AC and on the city tramway at 600V DC, one very significant innovation is the introduction of diesel trams for operation over non-electrified sections of line. This extends their reach beyond conventional electrified routes to rural single-track branches and diesel freight-only lines. Specifically, these vehicles are diesel hybrids: equipped with a diesel-electric engine, they are also able to work on the city tram network at 600V DC.

Each branch will operate to a regular interval 30-minute frequency, with connecting buses at stations along the route in line with the Taktfahrplan principle of bus and rail integration. Coupled with the enhanced journey opportunities, passenger demand on the network is predicted to grow by up to 50%.

Value for money

The total cost of the whole scheme is Euro 180million (£120million), made up of Euro 100million (£67million) for infrastructure and Euro 80million (£53milion) for new vehicles.

85% of the costs were borne by the Bundesland and federal government, with the remaining 15% contributed by the municipal authorities.

Key to the tram-train principle, and to the Kassel plan in particular, is maximum use of existing infrastructure to achieve greatest efficiencies and benefits. Diesel trams help to meet that goal by having the ability to fill in the electrification gaps as 'go-anywhere' vehicles, but the decision to choose them came about for three major reasons.

- Large infrastructure costs were avoided: the loading gauge in Zierenberg tunnel on the non-electrified Wolfhagen route to the west of Kassel did not allow for electrification without substantial rebuilding. This resulted in a capital cost saving of Euro 7.5million (£4.9million).
- In addition to the costs of rebuilding the tunnel, the capital spend to electrify the 30-km Wolfhagen route would have been around Euro 2million (£1.3million) per kilometre, not including ongoing operational expenditure, and unjustifiable in this case.
- Time and money would be saved in the planning process.

The above savings on the Wolfhagen route represent upwards of 55% of the total infrastructure costs of the entire project, and demonstrate, how much more expensive a fully electric system would be. Feasibility studies carried out between 2000 and 2003 focusing on whether to opt for electric-only vehicles or a mixed fleet containing diesel-hybrid versions as well, favoured the latter and resulted in the authority to proceed.

As an additional benefit, a short unelectrified freight-only chord at Kaufungen on the otherwise electrified Hessisch Lichtenau route could be brought into use to save eight minutes on the normal end-to-end journey time without any significant infrastructure work – an easy 'quick win'.

Comparison of diesel-hybrid and electric-only trams

	Diesel-hybrid tram	Dual-voltage electric-only tram
Number of vehicles	10	18
Power rating	600kW	600kW
Propulsion	diesel-electric: two roof-mounted six-cylinder MAN diesel engines, each delivering 375 kW tramway: 600 V DC	mainline: 15 kV AC tramway: 600 V DC
Number of traction motors	4	4
Acceleration from start	1.1ms^{2}	1.1ms^{2}
Maximum speed	100km/h	100km/h
Weight of a three-vehicle unit (when empty)	63.4t	59.8t
Weight of a three-vehicle unit (fully loaded)	85.2t	82.5t
Seating capacity	84 (plus 6 'tip-up')	84 (plus 6 'tip-up')
Standing capacity	139	139
Boarding height	360mm	360mm
Length over buffers / couplings	36.76m / 37.48m	36.76m / 37.48m
Width at maximum point	2.65m	2.65m
Minimum radius	22m	22m

Technical specification

Twenty-eight three-car vehicles were ordered for the project, 18 electric-only and 10 diesel hybrids. Built by Alstom, they are part of the Regio Citadis family. Both versions are visually very similar, and share many features for ease of maintenance. Crucially, performance is the same for both electric-only and diesel-hybrid vehicles – acceleration from start is 1.1ms^{2} in each case. A comparison of the vehicles is given in the table.

Transferability / applicability to UK

As stated above, conditions for tram-train have to be right, and given the small number of tram systems in the UK, let alone other complexities in the development of a scheme, it is clear that imitating the Karlsruhe model here is a harder task. The Sunderland extension of the Tyne & Wear Metro used some tram-train principles but employed the existing electric Metro vehicles, and areas including Greater Manchester and Teesside have been looking at the use of tram-trains. It would seem that in the UK context, diesel tram technology could help broaden tram-train's appeal, especially in increasing the affordability of light rail schemes, and where funding has been withdrawn owing to cost overruns as in the Leeds Supertram project. Potentially they combine the speed of a railway and the accessibility of a tramway, at a much lower capital cost than electric trams.

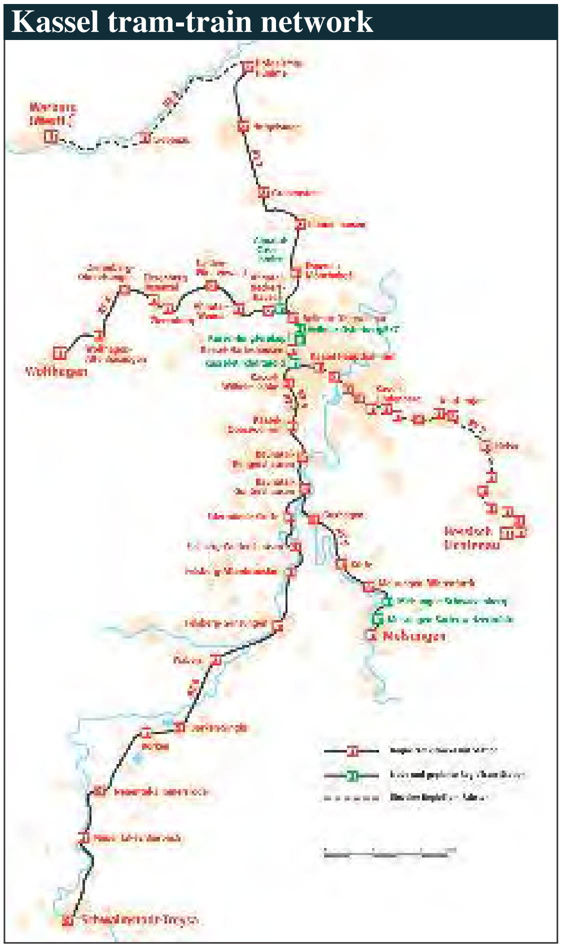
Joining up urban centres

First, taking advantage of a tram's ability to penetrate the urban centre, a tramway spur from the mainline to such 'honey pot' sites offers the opportunity to go right to where the customers want to go and encourage modal shift with seamless journeys. If Karlsruhe has shown that through journeys work with electric vehicles, then diesel trams prove that a potential station crucially need not be sited on an electrified Network Rail line – thus opening up the entire British railway network – nor would the tramway itself require electrification.

Blackpool illustrates the potential: diesel trams offer the prospect of linking up the South Fylde line with the tramway, thereby opening up many new journey opportunities and contributing to the area's regeneration. As no electrification would be necessary, major new infrastructure would be confined to connecting the two networks and restoring some of the double track on the railway section. There are also knock-on benefits to the local service: faster, more frequent

The diesel tram idea could be a low-cost alternative for branch lines such St Erth to St Ives, seen here. This is No 153329, which was released to traffic painted in a St Ives Bay livery and named *St Ives Belle* in a ceremony at St Ives. The vehicle is seen approaching Carbis Bay on its way to St Ives on the naming day, 4 December 2005.
Colin J. Marsden

The village of Weimar near Kassel, where light rail and heavy rail share tracks. On the left is a diesel-hybrid tram, on the right is a Stadler GTW DMU of the Kurhessen Bahn. *Heribert Menzel*



Kassel tram-train network

journeys and reduced wear and tear on the track thanks to tram running characteristics and lighter axle loads.

Again, this has been demonstrated in Kassel where the 30-km predominantly rural line to Wolfhagen has a mixture of stopping and semi-fast services, taking between 47 and 33 minutes to Kassel. Operating a diesel tram on the stopping services with its superior acceleration and braking performance has allowed five new stations to be served whilst maintaining existing end-to-end schedules. Conventional trains can then be more usefully deployed on semi-fast services.

Challenges

As in Kassel, electrification could be employed where it is essential, for instance in city centres and particularly sensitive areas, with diesel operation along converted local train routes or more open corridors. The same might be envisaged in Nottingham for example, with through services from Mansfield using a link at Bulwell to access the city centre.

It is also conceivable that diesel trams could be used on a self-contained tramway where costs are reduced through not having to electrify from the outset. Given our acceptance of buses in city centres, why are we not ready to tolerate diesel tram operation? Personal experience has shown a diesel tram to be perfectly acceptable: it is far quieter and has less visible emissions than any of the diesel trains operating in the UK. Queues of idling buses waiting in Manchester's Piccadilly Gardens, London's Oxford Street or any of the other increasingly congested UK cities underline the fact that all modes of transport are polluting. A central issue for debate, therefore, is where it is acceptable for that pollution to be produced: at the point of use as with diesel traction, or confined to a power station. Ever more sophisticated diesel engine technology and cleaner fuels such as Ultra-Low Sulphur Diesel mean that a modern diesel vehicle is coming ever closer to meeting the environmental acceptability standards of an electric.

Operational flexibility

The attraction of diesel trams does not merely lie in their ability to operate as urban street vehicles. With regard to rolling stock operation, in a climate where everything must be increasingly accountable, does it always make sense to run conventional trains on rural routes or a small shuttle service? Running a diesel tram over the St Erth – St Ives or Marks Tey – Sudbury branch, for example, could result in lower infrastructure operating and maintenance costs, as well as freeing up the conventional DMU for use elsewhere. A diesel tram-style service could also allow extra stops to be served, as suggested for the Tees Valley for instance (p50, last month). If more capacity is needed, several units can be coupled together (up to four can run as a 'train' in Kassel). Of course, the ultimate is full conversion of the line to tramway standards with simplification or even removal of signalling – driving on 'line of sight' – and again lowering track maintenance costs. Retaining the option of through running onto the mainline would open up many more possibilities, and also allow access to existing maintenance facilities elsewhere on the network if required.

The future

There are signs that the industry is looking towards an approach where operational and maintenance standards on a line are more closely dictated by its function and the type of traffic it sustains. We must be ready to accommodate this shift in focus if it secures the longer-term future of more lightly used lines and ensures they remain fit for purpose. Community railways are a prime example of this: if a certain route with a low line speed only sees a few passenger trains a day operated by Pacers and no freight, why could this service not be provided by a diesel tram with its attendant cost savings and, from the passengers' perspective, a more comfortable journey experience?

Diesel trams will not provide the answer in all cases, but they have clearly helped to provide new impetus to the tram-train concept as well as demonstrating their value as rail vehicles in their own right. At a time when the train-infrastructure interface comes under closer scrutiny, considerably lighter tram-type vehicles could contribute to a 'virtuous maintenance circle', and Network Rail's vision for a more reliable railway. In the effort to maintain and grow rail's attractiveness through 'joined-up journeys', and to ensure that each line is used as appropriately as possible, light rail technologies are likely to play an increasingly important role. Diesel trams are well placed to form part of that mix. **MR**

Following a year's internship in Germany with DB (German Rail) and a transport planning consultancy, Charles King joined the Transportation Division of Faber Maunsell as a rail transport planner. Last year, on behalf of ACoRP, he organised the tram-train study visit to Switzerland and Germany referred to in this article.

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Alstom to test onboard flywheel energy storage

18 January 2013

ENERGY: Alstom Transport and Williams Hybrid Power signed an agreement on January 17 to test Williams' energy storage technology on a Citadis tram.

Under the exclusive relationship, the two companies will adapt Williams' composite MLC flywheel energy storage. Trials will start in 2014, with a view to installing a prototype system on an existing vehicle by the end of that year.

Williams' flywheel technology was originally developed for the 2009 Williams Formula One car, and has since been introduced into London buses. It offers fuel savings of up to 15% by recovering braking energy that is normally lost as heat. The rotor flywheel is made from a composite material, which makes it safer than metal at high speeds.

Related News:

- European Commission backs regenerative braking R&D - 04.12.12
- Supercapacitor light metro train unveiled - 23.08.12
- Genève tram trial assesses supercapacitor performance - 07.08.12
- Supercapacitor energy storage for South Island Line - 03.08.12
- DMUs to test regenerative braking - 18.06.12
- Energy storage offers Macau metro 10% saving - 15.06.12
- Hydrogen fuel cell tram unveiled - 19.10.11
- Flywheel railcar to operate demonstration commuter service - 14.01.11
- Fuel cell tram trial - 24.06.10

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Alstom Transport
48, rue Albert Dhalenne
93482 Saint-Ouen Cedex France
Telephone: +33 (0)1 57 06 90 00

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Optimized access for all

With its full low floor and wide gangways, Citadis Dualis is the first tram-train vehicle certified according to STI PRM* standards.

Passenger comfort

Citadis Dualis offers many options dedicated to passenger comfort, depending on the profile of the line served. Among the possibilities are toilets, more comfortable seats, window shades and umbrella racks...

Citadis Dualis makes on-board comfort a priority.

Operating tools

Citadis Dualis also offers anti-vandalism and passenger-counting options to optimize public transit operations for maximum vehicle availability.

Modular Design

Citadis Dualis may be configured to the needs of each operator.

Urban or peri-urban configuration, number of doors per side, interior spaces... the design and layout of your Citadis Dualis are modular to fit the type of itinerary.

---

* Excluding the toilet option

4 DEGREES OF FREEDOM

LENGTH

42 Meters and 52 Meters

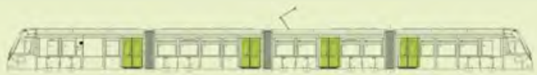
WIDTH

2.4 Meters and 2.65 Meters

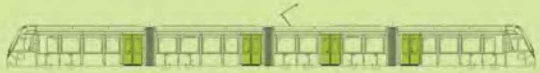
ELECTRIC POWER SUPPLY

Dual voltage 750 Vdc / 25 KVac 50 Hz
Or dual voltage 750 Vdc / 1500 Vdc

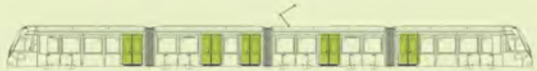
INTERIOR FITTINGS



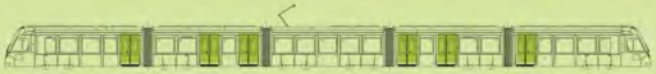
- Length: 42 m
- Width: 2.4 m
- 4 doors
- 93 seated places
- 141 standing places



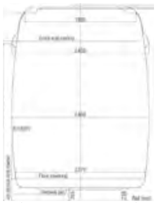
- Length: 42 m
- Width: 2.65 m
- 4 doors
- 98 seated places
- 153 standing places



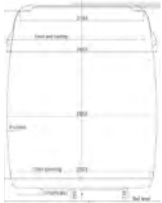
- Length: 42 m
- Width: 2.65 m
- 5 doors
- 92 seated places
- 159 standing places



- Length: 51.5 m
- Width: 2.4 m
- 6 doors
- 116 seated places
- 176 standing places



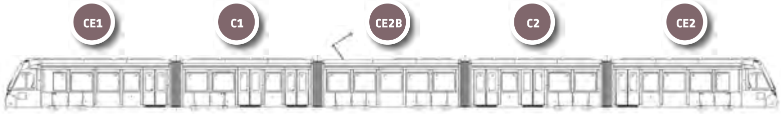
2.4 meters



2.65 meters

CAPACITIES

	VERSION 2.65 M 4 CARS 4 DOORS	VERSION 2.65 m 4 CARS 5 DOORS	VERSION 2.40 m 4 CARS 4 DOORS	VERSION 2.40 m 5 CARS 6 DOORS
Seats + Tip-up seats				
CE2	18 + 2	18 + 2	16 + 2	16 + 2
C2				20
CE2B	32	32	32	40
C1	24 + 2	20	22 + 3	20
CE1	18 + 2	18 + 2	16 + 2	16 + 2
Total	92 + 6	88 + 4	86 + 7	112 + 4
Passenger in Wheelchair space	2	2	2	2
Bicycle rack	1	0	1	0
Luggage rack	1	0	1	0
Total passengers				
4 persons/m²	251	251	234	292
6 persons/m²	330	332	307	382
8 persons/m²	410	414	381	472



TECHNICAL **SPECIFICATIONS**

Type	Articulated – 4 to 5 car bodies
Length	4 car bodies: 42 m 5 car bodies : 52m
Width	2.65 m (4 car bodies) or 2.40 m (4 or 5 car bodies)
Height	3.5 m
Floor height (4 pers/m^2 + seats folded, new wheels) · Access (gap-filler) · Corridor central part · Corridor above bogies	 370 mm 405 mm 537 mm
Multiple Unit	Up to 3 units (MU3) with 4 car bodies
Structure · Compression · Passive safety	 600 kN complies with standards EN12663 and EN15227
Performance · Maximum speed · Maximum acceleration from start up	 100 km/h 1,09 m/s^2 from 0 to 40 km /h (base version)
Braking · Types · Maximum Emergency braking deceleration	 Electric, Electrohydraulic and Electromagnetic 2.8 m/s speed ≤ 70 km/h 2.5 m/s speed > 70 km/h
Weight · Tare weight · Maximum load per axle (6 persons/m2 + seats extended)	 ≈77 t (4- car vehicule) 11.5 t
Traction · Type · Continuous Motor power	 IGBT, 3-phase permanent magnet synchronous motor Motor 6 x 150 kW
Train Control / Command	Redundant MVB network / WTB Cabled commands for safety functions
Electric power supply	Dual voltage 750 Vdc / 25 kVac 50 Hz Dual voltage 750 Vdc / 1500 Vdc
Auxiliary power	400 Vac /50 Hz 24 Vdc
Minimum curve radius	25 m
Capacity in EL4 (4 pas/m^2) · 4-car vehicle · 5-car vehicle	Fixed seats / Total 86-92 / 234-251 112 / 292
Corridor width	600 mm (2.65 m version)
Passenger access width	Double sliding door / 1,300 mm passage
Platform access	Fill-gap
Passenger Information · Base · Option	 Interior and exterior LED display screens + audio TFT screens

OPTIONS

DESIGN OPTIONS	Length (in m.)	42	42	42	52
	Width (in m.)	2,65	2,65	2,4	2,4
	Number of cars	4	4	4	5
	Number of doors per side	4	5	4	6
	Luggage space	●	●	●	●
	Bicycle space	●	●	●	●
	Retractable steps	●	●	●	●
	Maximum number of doors per side	5	5	5	7
CONTRACTUAL OPTIONS	Toilets	●			
	Fixed steps for the doors	●	●	●	●
	Supply and installation of passenger-counting system	●	●	●	●
	Lengthwise umbrella rack	●		●	
	Exterior livery	●	●	●	●
	Trash receptacles	●	●	●	●
	Passenger window shade	●	●	●	●
	More comfortable seats (cannot be combined with anti-vandalism option)	●			
	Anti-vandalism (cannot be combined with more comfortable seat option)	●			

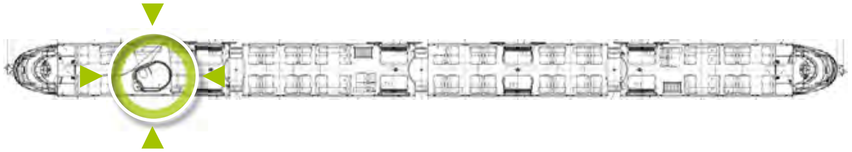
COMFORT **OPTIONS**

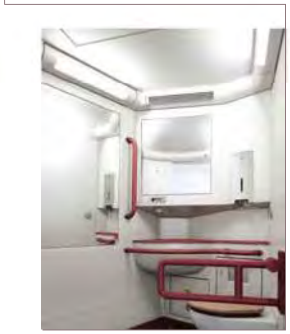
TOILET OPTION*

The toilet option* is offered aboard the CITADIS DUALIS in a suburban configuration (2 m65 in width) in order to improve passenger comfort for trips that exceed 30 minutes. This is a unique option in a tramway-type LRV. Two variants are possible for this option:

- Factory-fitted toilets,
- Preparation for toilet integration at a later time (for example in the case of a line extension)

* Option non-certified STI PRM





LENGTHWISE UMBRELLA RACK OPTION

CITADIS DUALIS can also be equipped with lengthwise overhead racks. These allow passengers to put small objects, umbrellas, jackets... above their seats and also improve passenger comfort in freeing up space.

TRASH RECEPTACLE OPTION

Trash receptacles can be installed as an option aboard the CITADIS DUALIS. They facilitate maintaining a high level of on-board cleanliness, improving both the trip's ambiance and the cleaning work.

PASSENGER WINDOW SHADE OPTION

Passengers are able to adjust sunlight to what's comfortable.

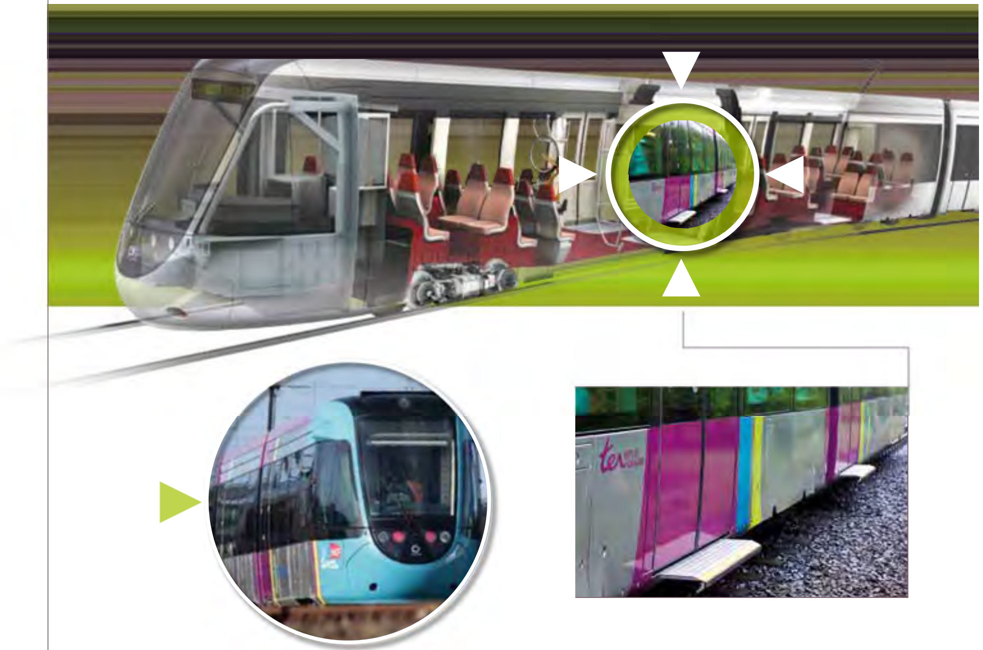
MORE COMFORTABLE SEAT OPTION (CANNOT BE COMBINED WITH THE ANTI-VANDALISM OPTION)

Improved seating and an added headrest offer passengers greater travel comfort.

TECHNICAL **OPTIONS**

FIXED STEPS OPTION

Removal of the retractable steps (standard edition) in order to reduce passenger exchange times at stations.
This option requires an appropriate infrastructure.

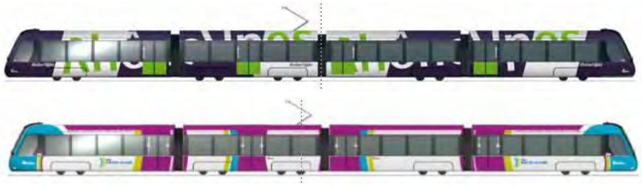


PASSENGER COUNTING OPTION

All vehicle accesses are equipped with a system that makes it possible to note passengers getting on and off.
The number of passengers aboard is thus known at all times.
This is an essential element for tram-train operations.

INDIVIDUALIZED EXTERIOR LIVERY

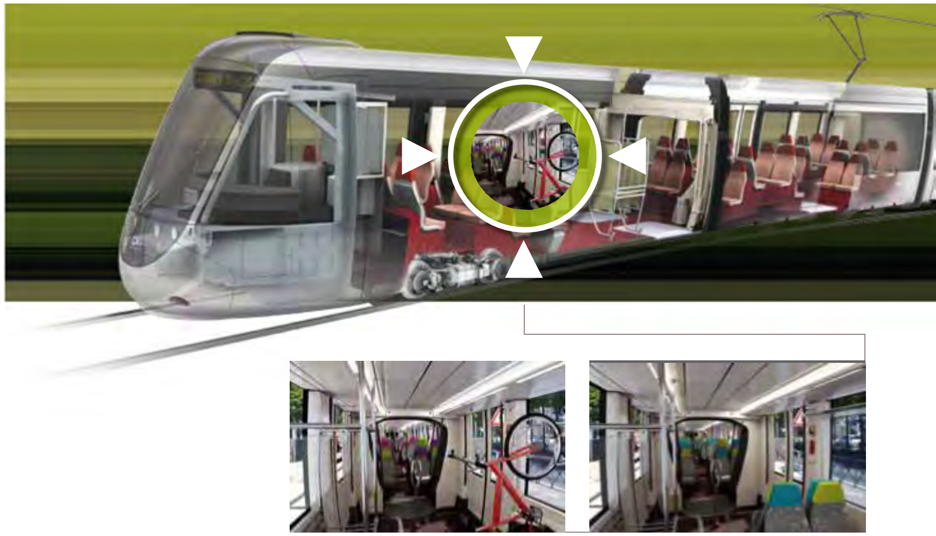
To facilitate its integration in the regional landscape, the livery of the CITADIS DUALIS can be individualized with the colors of the region.



ANTI-VANDALISM OPTION

CITADIS DUALIS’s anti-vandalism resistance can be reinforced with an interior and exterior film protection on the car.

BICYCLE SPACE / LUGGAGE SPACE (OPTION DEPENDS ON THE BODY CAR’ DESIGN)



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Lyon tram-train service launched

25 September 2012

FRANCE: SNCF began operating tram-train services from Lyon Saint-Paul to Sain-Bel on September 24, following an official opening ceremony two days before.

On weekdays there is now a service every 30 min, increasing to every 15 min between Lyon and L'Arbresle during the peaks. It is hoped that ridership will double from present levels to 13 200 passengers a day by the end of 2012.

It is the first of three routes from Lyon Saint-Paul serving the city's western suburbs that are to be converted to tram-train operation. Subject to obtaining the necessary safety approvals, Alstom Citadis Dualis vehicles are expected to begin operating to Brignais in December, using a new east to south chord at Tassin, followed by the route to Lozanne.

Total cost of the infrastructure work required for the west Lyon tram-train programme is estimated at €150·2m, of which €91·4m is being provided by the Rhône-Alpes region, €16·5m by the French government and €15·9m by infrastructure authority RFF. The Greater Lyon authority has contributed €13·1m, the Rhône *département* €12·5m and SNCF €800 000.

Infrastructure work has comprised doubling some sections of single line, lengthening passing loops, track renewals, electrification and resignalling. Platforms have been rebuilt to provide level boarding, while a €35m station modernisation programme has included the installation of a real-time passenger information system and improved facilities for cyclists. A new station has been built at Lentilly-Charpenay, and Dommartin-Lissieu relocated; both now provide park and ride facilities.

Within a €650m framework agreement between SNCF and Alstom for up to 200 vehicles, a fleet of 24 Citadis Dualis tram-trains has been acquired for €100m, entirely funded by the Rhône-Alpes region. The 42 m long vehicles have 100 seats and can accommodate 150 standing passengers, with a maximum speed of 100 km/h.

Maintenance is undertaken at a new facility built on a 1·5 ha site near L'Arbresle station, funded by the Rhône-Alpes region (€11·48m) and SNCF (€3·82m).

Related News:

- Electrification contract for Bordeaux tram-train project - 25.02.13
- Alstom launches North American light rail vehicle with Ottawa contract - 14.02.13
- T2 completes Dijon tram network - 18.12.12
- Le Havre celebrates tramway opening - 12.12.12
- Tours 'architecture in motion' tram unveiled - 02.10.12
- UK must start developing tram-train now - 26.06.12

Tramwave on test

Tramwave is being tested on a 600 m test section in Napoli.

ITALY: Ansaldo STS is testing ground level power supply technology for street-running tram tracks, eliminating the need for overhead wires. Known as Tramwave, the equipment is undergoing live trials along a major thoroughfare in Napoli. More than 600 m long, the test section has allowed Ansaldo STS to monitor and analyse performance of the system under actual operating conditions with heavy road vehicles passing over it.

The test site forms part of a recently completed extension of the Emiciclo Poggioreale – Via Stadera tram route. It has attracted considerable interest, with numerous delegations from European and Asian countries visiting Napoli to see the system in action. Ansaldo STS has also used the site to obtain safety certification.

Ansaldo STS initially tested Tramwave on a 400 m elevated track located in its own factory premises in Napoli. Experience built up with this installation gave the company confidence to experiment with a live installation on a public road.

How it works

The design makes use of magnetic collector shoes attached to the tram bogies. The shoes are fitted with copper and graphite contact surfaces which pass over steel plates affixed to a modular box-shaped contact line laid between the running rails. The permanent hybrid magnets in the shoe lift a ferromagnetic belt housed in a continuous module located below the steel plates, where a 750 V DC conductor rail and an earthed contact are also enclosed.

Each element of the module is typically 3 m or 5 m long. The steel contact plates are each 500 mm long and are insulated from each other. As each portion of the belt is lifted by the magnets on the shoe, it touches the plate, allowing current to pass through to the tram's traction equipment.

Energy only passes through the plates when the collector shoe is present, and the supply line voltage returns to zero as soon as the tram has passed over each segment. The live section beneath each power collecting bogie is less than 2 m long.

Ansaldo STS sees a large market for the technology, not least because of the huge interest in tram projects in many countries, but also because many cities have areas of historical or architectural importance where a catenary-free tram line would appeal to planning authorities.

The company notes that requests for wire-free systems have come from Qatar and Dubai. It also says that interest has been shown by countries where the frequency and intensity of weather phenomena render overhead wires impractical, for example in Taiwan.

The AnsaldoBreda Sirio trams used to test Tramwave are fitted with an underfloor pick-up shoe.

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Rhein-Neckar Verkehr orders more supercapacitor trams

05 April 2011

GERMANY: Rhein-Neckar regional transport operator RNV has ordered a further 11 low-floor Variobahn trams for €33m, Bombardier Transportation announced on April 4.

They will be fitted with Bombardier's Mitrac Energy Saver technology, which uses roof-mounted double-layer supercapacitors to store electricity regenerated during braking for reuse when accelerating. Trials in Mannheim have demonstrated a reduction in energy consumption of up to 30% using Energy Saver, which is currently fitted to 19 RNV trams.

Delivery of the latest batch of air-conditioned and wheelchair-accessible cars is scheduled for January to June 2013. 'Starting in 2013, we will be operating entirely with modern, low-floor vehicles on the 200 km railway and tram network of RNV', said Martin in der Beek, Chief Technical Officer at RNV. 'Together with ongoing accessibility upgrades at stops in Ludwigshafen, Mannheim and Heidelberg as well as the surrounding area, we are contributing to the increasingly important concept of universally accessible public transport.'

The latest order is an option on a contract signed in 1998. The trams are to be built at Bombardier's Bautzen plant, with bogies from Siegen and electrical equipment from Mannheim.

Related News:
Supercapacitor light metro train unveiled - 23.08.12
Genève tram trial assesses supercapacitor performance - 07.08.12
Supercapacitor energy storage for South Island Line - 03.08.12
Dresden Messe tram extension opens - 02.06.11
First Stadler Variobahn arrives in Potsdam - 31.05.11
Supercapacitors to be tested on Paris STEEM tram - 08.07.09
Primove catenary-free induction tram - 23.01.09
Ultracapacitors on test - 08.01.09
SuperCap tests complete - 18.03.08
UltraCaps win out in energy storage - 01.07.06

Links:
Rhein-Neckar-Verkehr

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Jeremie Desjardins
Business Leader
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Augsburg pilot project: a case study

Videos

PRIMOVE: Game-changing turnkey solution for tram systems

More information

German Federal Ministry for Transport, Building and Urban Development (BMVBS)
Augsburg Transport Authority (STAWA)
Tüv Süd

Catenary-free operations for trams

In September 2010, Bombardier Transportation installed the contactless and catenary-free PRIMOVE system for trams on a 800-metre section of Line 3 on the Augsburg trade fair centre. The pilot project is co-funded by the German Federal Ministry for Transport, Building and Urban Development (BMVBS) and realised in cooperation with the Augsburg Transport Authority (Stadtwerke Augsburg Verkehrs GmbH) with the aim of demonstrating reliable operation under the real conditions of daily operation in an urban environment.

Bundesministerium für Verkehr, Bau und Stadtentwicklung

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Stadtwerke Augsburg

Demonstrating safe high power inductive charging for trams

Phase 1: Winter 2010 – Fall 2011

One Bombardier bidirectional low-floor tram was fitted with two PRIMOVE power receivers (pick-up coils) to capture the inductive power that is transferred from eight-metre cable segments laid between the rails underneath the ground. Inverters along the track wayside are connected to a 750 Vdc power supply network.

Once supplied with energy, the cables create a magnetic field that is sensed by the tram's pick-up coils and turned into an electric current that propels the tram. Segments not covered by the tram are not activated.

Energy storage solution for added energy efficiency
Two energy storage devices were also mounted on the tram roof. Every time the vehicle brakes are applied, super capacitors store the released energy for later use. When installed on light rail vehicles, the system reduces energy consumption by 30%, thereby significantly minimising electricity costs.

Phase 2: Fall 2011 – Summer 2012
In the second phase of the project, a PRIMOVE-equipped bus and minivan will undergo tests to demonstrate the intermodality of the system. Multimodal charging compatibility has already been demonstrated with a PRIMOVE-equipped road vehicle that recharged using the same charging infrastructure installed for the tram. Further tests will continue until the end of the summer 2012.

May 31, 2012: PRIMOVE international media event and world premiere of inductive technology
Bombardier welcomed more than 80 international journalists and guests to the world premiere of inductive technology for all e-vehicles at the PRIMOVE test track in Augsburg.

To download the press release, please click here.

To view the video, please click here.

Bombardier test project involves induction technology

BY FRANÇOIS SHALOM, THE GAZETTE JANUARY 10, 2013

An artist's conception of Bombardier's new electric bus which has its battery recharged through a capacitor under bus stops.

MONTREAL — There's no budget, no timeline, no proven technology, much less shovels in the ground or even a signed contract.

But it's substantially more than an idle dream.

Montreal's Île-Ste-Hélène is scheduled to be the North American test site this year for Bombardier Inc.'s Primove pilot project, a technology that is being tested at four sites in Germany, where the firm's rail division is based.

Primove's mandate is to develop electric mass-transit propulsion systems, but not the vehicles themselves.

Intended to bypass the conventional notion of electric buses and trolley buses powered by cumbersome batteries, Primove rests on an inductive transfer of power from ground-based electrical power sources to very small batteries placed under, not in, the bus.

Sensors on the vehicles would store the energy emitted by the electro-magnetic field, but only in small quantities, feeding the bus or trolley sufficiently to reach the next power source a short distance away. The system can charge while the vehicle is in motion or at rest.

“You bury power stations capable of charging rapidly, even instantly — we’re talking seconds — so that you don’t need to resort to (lengthier) conventional power boost systems currently on the market” like hybrid and electric vehicles, said Bombardier Transportation spokesperson Marc Laforge.

Burying the infrastructure underground eliminates not only long battery-recharging sessions but also the visual pollution of vast meshings of overhead cables that tramway catenaries and pantographs require, he added.

“It’s kind of the opposite principle — (Primove is designed to) store the energy source out of sight,” Laforge said.

To get there, though, Bombardier will need three partners; bus manufacturers, Hydro-Québec and mass transit agencies.

“The beauty of this project,” said Laforge, “is that the most interested party in North America is in Canada, in fact Montreal and the Société de transport de Montréal. For us at Bombardier, that’s perfect.”

But the STM’s enthusiasm was tempered, to say the least.

“Yes, absolutely there are discussions between us and Bombardier, but it’s very preliminary,” said spokesperson Isabelle Tremblay.

“There’s a general interest on our part concerning, in particular, rapid charging. But it’s at the exploratory stage right now, and our focus is on our long-term goal of buying only electric vehicles by 2025, whatever form that may take.”

“Bombardier is working on induction technology, which may be great, but we’re looking at everything available on the market, including a Chinese electric-charge technology that works very well.”

“But this is at the talking stage only — there is no budget dedicated to this, no deadline,” Tremblay said. “On the other hand, we’re listening and we’re interested.”

Laforge said that “if all goes well, we should do this pilot project this year on Île-Ste-Hélène,” and that Bombardier has approached Hydro-Québec and various bus manufacturers, including Quebec’s Nova Bus, which supplies the STM exclusively. The St-Eustache bus maker is selling 1,688 hybrid buses to the STM and Quebec’s eight other public transport agencies.

Gilles Dion, president and CEO of Nova Bus, said that he has discussed the Primove project with Bombardier “frequently for the last year or two.”

“It’s a fantastic initiative on Bombardier’s part, and I think there’s great potential for it.”

“We’re working to see how we could turn this trial technology into electric vehicles.”

“Are we going to be able to conduct tests this year? If not, it will be by next spring.”

But Dion noted that politics will play a role in its implementation.

Bombardier and Nova Bus had received financial commitments for the project after lengthy talks with the previous Liberal government led by Jean Charest. But discussions must now be restarted under Pauline Marois's Parti Québecois government to make sure the commitments conform to its policies and goals.

"I'm assuming that the (undisclosed) sums earmarked for this project will still be available, but everyone has to be on the same page once again, including Hydro-Québec, which will supply the electric system."

Hydro-Québec spokesperson Mathieu Rouy confirmed the utility has held some preliminary meetings with Bombardier and the STM to discuss the project, but said he could not comment further until the new government officially announces its policy for electric vehicles.

Between 2011 and 2020, Rouy said in an email, the Charest government had set aside "five envelopes of $100,000 each attributed by Hydro-Québec to projects linked to the electrification of transportation modes. To date, only one envelope has been attributed (to Laval)."

"As we speak, this program is maintained by the current government, so there remain four envelopes of $100,000 to be attributed."

Bombardier's Jérémie Desjardins, who heads the Primove project in Europe, told sources there that the technology has huge implications for Bombardier. If successful, it could lead to commercialization in related automotive fields, including cars and trucks.

But Bombardier's success in non-rail mass vehicles has been mitigated in recent years in Europe. Two French cities, for instance, Caen and Nancy, scrapped their Bombardier-provided tramways that suffered much higher than normal rates of breakdowns and failures after only a few years — three decades before their anticipated retirement.

But Dion said that the Primove technology is "very, very, very promising."

"That's why we're all looking at it so closely."

fshalom@montrealgazette.com

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Primove induction powered tram trial proves a success

12 June 2012

GERMANY: Bombardier Transportation has successfully completed testing of its Primove catenary-free power system on a branch of the Augsburg tram network.

Primove uses cables between the rails to produce magnetic fields which induce electric current for traction power in pick-up coils mounted underneath the vehicle.

The tests were carried out using a modified Bombardier low-floor tram. The Primove 200 kHz induction loops were installed on an 800 m spur line which is only used in public service during events at the city's exhibition centre.

Augsburg transport operator AVG does not plan to deploy Primove, as it has a modern fleet of conventionally powered trams, but the federal government has awarded funding for Bombardier and Braunschweig transport operator BSVAG to undertake in-service trials with two electric buses which will run on a 12 km route.

- For more details of the Primove trials and Bombardier's vision for e-mobility, read the July 2012 issue of *Railway Gazette International*

Related News:

Freedom takes Flexity to the North American tram market - 04.10.11
Bombardier to test wireless trams in Augsburg - 26.05.10
Primove catenary-free induction tram - 23.01.09

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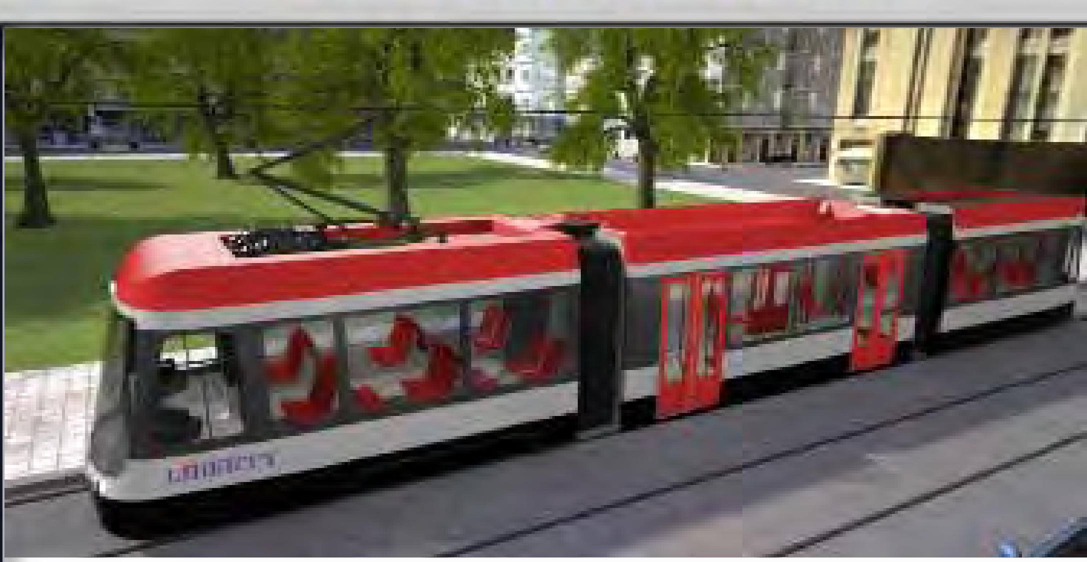

Above: Liberty Streetcar with three passenger compartments.

Left:
Interior of Liberty Streetcar with customizable seating arrangements.

Right:
Interior of Liberty Streetcar with just a single step to high-floor section.

Left:
Exterior of Liberty Streetcar with sleek, modern design.

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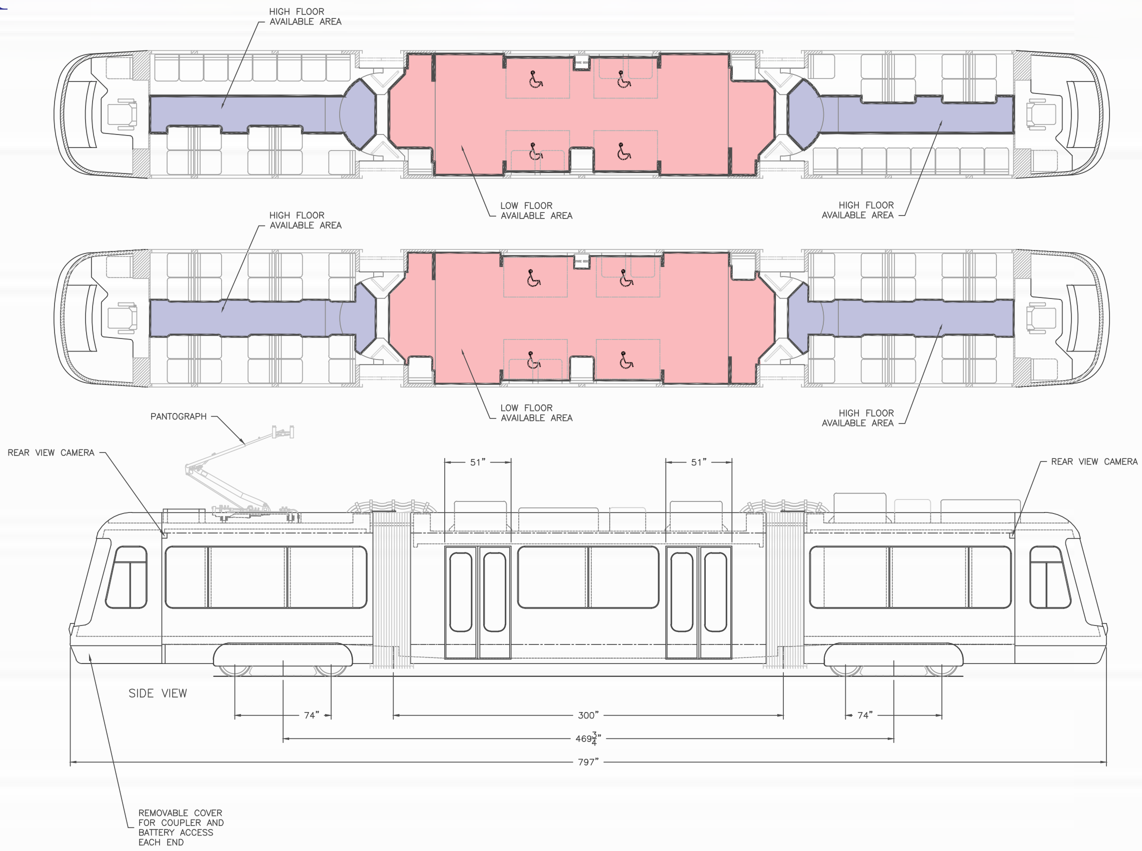
Car Width
8 Feet
(2.45 meters)

Car Width
8 Feet, 8 Inches
(2.65 meters)


HIGH FLOOR AVAILABLE AREA
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HIGH FLOOR AVAILABLE AREA
PANTOGRAPH
REAR VIEW CAMERA
51"
51"
REAR VIEW CAMERA
SIDE VIEW
74"
300"
74"
469¾"
797"
REMOVABLE COVER FOR COUPLER AND BATTERY ACCESS EACH END

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Liberty Class Streetcar - Technical Specifications

Track Gauge	Standard 4 Feet, 8.5 Inches	
Boarding Height	13.75 Inches (350mm)	
Power Supply	750 V DC (Max. 925 V DC, Min. 525 V DC)	
Low-Voltage Power Supply	24 V DC	
Motors	4 x 65 kW or 4 x 80 kW	
Maximum Speed	44 mph (70 km/h)	
Vehicle Length	66 Feet, 5 Inches	
Max. Height (w/o Pantograph)	10 Feet, 6 Inches	
Wheelbase	39 Feet	
Weight of Car Empty	63,960 lbs (without off-wire capability)	
Acceleration	3.0 mphps (1.3m/s2)	
Brake Deceleration	3.0 mphps	
Emergency Brake Deceleration	5.0 mphps	
Maximum Grade	9%	
Vehicle Width	8 Feet (2.46 m)	8 Feet, 8 Inches (2.65 m)
Percentage of Low-Floor Area	71%	73%
Total Seating Capacity	41 Passengers + 1 Operator	47 Passengers + 1 Operator
Maximum Capacity (AW3)	127 Standees + 41 Seated + 1 Operator = 169	135 Standees + 47 Seated + 1 Operator = 183
Maximum Capacity (AW4)	170 Standees + 41 Seated + 1 Operator = 212	181 Standees + 47 Seated + 1 Operator = 229

Features of the Car Include:

- Single step design between low-floor and high-floor sections
- Over 70% low-floor
- BROOKVILLE soft-ride trucks proven under 49 streetcars in USA
- Meets Buy America requirements

Standard Options:

- Two body widths
- Different door configurations
- Various seating configurations
- Various body trim/paint schemes
- Multiple Unit operation (MU)
- Propulsion upgrades for higher speed
- Energy Storage System (ESS) for periods of off-wire operation

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Your first look at the streetcars to roll from Union Station to Oak Cliff come 2014

By ROBERT WILONSKY

Staff Writer

Published: 10 September 2012 11:07 AM

Editor's note: This item originally appeared on the Transportation blog.

New, 11:02 a.m.

When last we asked about the downtown-to-Oak Cliff streetcar project, scheduled to close the Houston Street Bridge sooner than later for construction, we were told there was a shortlist of would-be providers, and that the Dallas Area Rapid Transit board was *this close* to settling on a manufacturer. At last, we have a would-be winner: Brookville Equipment Corporation out of Brookville, PA, which DART's Committee-of-the-Whole is scheduled to okee-doke tomorrow before the full board gives its final stamp of approval later this month.

As you'll see below in the PowerPoint prepped for the August 28 rail committee meeting, there were three companies that bid on the project: Brookville Equipment Corporation, Inekon and CAF, with the 94-year-old Brookville coming up the winner by offering to build two streetcars for $9,422,837 (give or take a "5-percent supplemental work contingence"). Others were interested, but balked in part because of the small size of the order: two cars.

As you'll note, Brookville only makes one modern streetcar, the Liberty, which is what Brookville proposed to Dallas, says Joel McNeil, who heads up the company's sales division. He's not prepared to delve into further specifics — "because it's not official and the board still needs to vote on it" — but he does answer a few, ya know, general questions about the streetcar itself. Such as:

"The cars are customized to a city's needs, so a seating capacity can be altered on how they want to lay out the seats," he says when asked about seating capacity. "A typical 66-foot-long car has between 41 and 47 seated passengers depending on how the customer specifies it, then you have a capacity of between 120 and 130 standing."

And, no, it won't be green. "We build a vehicle for what the customer wants, so they get to pick the exterior color, the interior layout, the color scheme. It's all dependent on how the city wants to handle it." One car is due in May 2014; the second, by September 2014.

Tomorrow the DART committee-of-the-whole is also scheduled to forward to the board a contract for the design-build portion of the streetcar project, which will go to …

… a joint venture between Alameda, California-based Stacy and Witbeck, Inc. and Dallas-based CARCON Industries & Construction. The contract's worth $27,963,520 — $23 million, of course, coming from those federal Transportation Investment Generating Economic Recovery (TIGER) grant funds, with the rest coming from regional toll funds. Says the contract, "The term of the contract is completion of the work by October 31, 2014." As for the route, for those who still have questions …

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Kaohsiung picks CAF to build catenary-free trams

07 January 2013

TAIWAN: Kaohsiung City Government's Mass Rapid Transit Bureau announced on January 4 that it had selected a consortium of CAF and Evergreen Construction to build the first stage of the city's catenary-free circular light rail line.

Now expected to cost NT$15·6bn, the 22·1 km route with 36 stops will link the main station with business, shopping and residential areas, as well as major developments around the harbour that are due to open during 2014. It will incorporate portions of Taiwan Railway Administration's existing Lin Gang East and West freight railways, as well as roadside reservations, and will interchange with both of the city's metro lines.

After proposing a privately-funded BOT concession in 2011, the city decided last year to manage the project through conventional procurement. New bids were called in November, with two offers being received by the December 17 deadline. The other bid came from a consortium of Ansaldo STS, AnsaldoBreda and New Asia Construction & Development Co.

The NT$5·7bn turnkey contract for the 8·7 km phase one covers detail design and construction of all civil engineering works, including the 1 435 mm gauge track, power supplies and the rolling stock. With much of the land already acquired, construction of this section is due to be completed by October 2014. Phase two is being co-ordinated with the reconstruction in tunnel of TRA's existing cross-city main line, and is due to follow by December 2017.

CAF is to supply a fleet of Urbos low-floor cars 2 650 mm wide, equipped with an onboard energy storage system that will be recharged at intervals along the line. This will avoid the need for either overhead catenary or an underground inductive power supply. Traction voltage has been specified at 750 V DC.

Services are expected to operate from 06.00 to 23.00 each day, with headways ranging from 15 min off-peak to every 6 min at peak times. Ridership on the completed route is projected to reach 87 000 passengers/day in 2021.

Related News:

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Zaragoza extends tram network - 20.12.12
Kaohsiung tenders catenary-free light rail project - 08.10.12
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Zaragoza tram Line 1 enters service

26 April 2011

SPAIN: The first phase of Zaragoza tram Line 1 entered service at 04.52 on April 19, following successful completion of trials which started in November last year.

The initial 6·4 km section of the north-south route links Plaza Paraíso on Gran Vía with Valdespartera and has 13 stops. Work on Phase II connecting Gran Vía to Parque Goya in the north is due to start in July and will last for around 24 months (RG 10.10 p51).

The 12·8 km project with 25 stops is being implemented by the Traza consortium of Tuzsa, CAF, FCC Construcción, Acciona, Ibercaja and Concessia at a cost of €400m and should be completed in June 2013. Traza will operate the line for 35 years.

A fleet of 21 Urbos 3 trams has been supplied by CAF. The vehicles are 33 m long and 2 650 mm wide with capacity for 200 passengers, comprising 54 seats and 146 standees. The trams are equipped with CAF's onboard ACR ultracapacitor energy storage system for catenary-free operation, which will be used in the city centre once Phase II is completed.

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Genève tram trial assesses supercapacitor performance - 07.08.12
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CAF named preferred bidder to supply new Midland Metro trams - 02.02.12
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Links:

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Zaragoza extends tram network

20 December 2012

SPAIN: Line 1 of the Zaragoza tram network grew by a further 844 m on December 20, with the opening of the section from Plaza de España to César Augusto and Plaza del Pilar. Extension of the network into the heart of the old city has also seen a further addition to Spain's longest section of catenary-free tram route.

Opening to Plaza del Pilar is expected to increase weekday ridership by 4 000 to 50 000 passengers a day on Line 1, now running for a total of 7·56 km from Mago de Oz in the southern suburb of Valdespartera. Weekday ridership is forecast to double with the opening of the final section to Parque Goya north of the city centre, now expected to enter service in April 2013.

Extension of the tram route to Plaza del Pilar has involved an extensive programme of improvements to the urban fabric, including the creation of a total of 29 175 m^2 of pedestrian areas. Utilities such as water, gas and electricity are now housed in a new service tunnel running beneath Avenida César Augusto.

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Seville goes catenary free

THE Spanish city of Seville is to remove the catenary from its only light rail line because it interferes with religious processions through the streets - part of the 1.6km line runs alongside the cathedral. CAF, which supplied five LRVs to Seville, will install its rapid-charge accumulator (ACR) system on the line and in the vehicles (IRJ June 2009 p24).

Short sections of catenary will remain at each stop to allow LRVs to be charged, which takes only 20 seconds. This will provide sufficient power to allow 600m of catenary-free operation between stops. Energy is also fully recovered during braking.

This is the first commercial application of ACR. However, about half of the light rail network being built in Zaragoza will be equipped with ACR.

THE first of 27 LRVs being supplied by CAF to Edinburgh was on show at BCN Rail. The 42.8m-long vehicles have a high-quality interior with leather seats, plenty of room for luggage as the 18.5km line will serve the airport, and a totally flat floor. Glass doors in the centre of the vehicle enable it to be split into two so that part of the vehicle can be shut off to passengers to improve security late at night.

Originally published October 26, 2011 at 6:36 PM | Page modified October 26, 2011 at 6:39 PM

Local firm wins bid to assemble streetcars

The First Hill streetcars in Seattle will be assembled here by 20 local workers at Pacifica Marine instead of being imported from Europe, as happened with the three South Lake Union streetcars.

By Mike Lindblom

Seattle Times transportation reporter

The next streetcars in Seattle will be assembled here by 20 local workers instead of being imported from Europe, as happened with the three South Lake Union (SLU) vehicles in 2007.

Seattle-based Pacifica Marine has been chosen to assemble six First Hill streetcars, to carry passengers starting in late 2013. The route goes from the International District/Chinatown light-rail station to Broadway, where the Capitol Hill station will be done in 2016.

The rail cars will be able to run 2 ½ miles on battery power and regenerative braking — so they draw electricity from overhead wires heading up to Capitol Hill and go wireless on the return to Chinatown.

This reduces conflicts between overhead streetcar and electric trolley-bus wires and should save energy and maintenance costs in the long run, said Ethan Melone, city streetcar-project manager.

The new jobs would pay $15-$30 per hour, under contract with the International Association of Machinists and Aerospace Workers.

The trains are designed by Czech-based Inekon, which built the SLU fleet. Exact details of the partnership are being worked out, but probably the car bodies will be imported from the Czech Republic, for final assembly, testing and maintenance in Seattle, using mostly North American components, according to Bill Patz, president of Pacifica. He said the plant here would "evolve" so that eventually, as local crews gain expertise, rail cars could be built entirely in Seattle.

More jobs could be added if the partnership wins contracts in some of the 20 or so other U.S. cities adding streetcars, supporters said.

Mayor Mike McGinn and City Council President Richard Conlin announced the deal Wednesday. Transit is one reason the city continues to attract employers, including Amazon and the Brooks athletic-shoe company, McGinn said.

The $130 million First Hill line is already funded by Sound Transit sales taxes that voters approved in 2008.

Since the 1990s, Pacifica assembled and retrofitted more than 65 Spanish-designed Talgo rail cars for the Amtrak Cascades line, said Patz. The Talgos are distinctive because they tilt based on track curvatures, improving comfort on fast turns. But right now, the company has an "empty shop" in the Duwamish area, said Patz.

Bid prices weren't announced Wednesday, but modern streetcars and light-rail cars are worth roughly $4 million each.

Mike Lindblom: 206-515-5631 or mlindblom@seattletimes.com

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Czech trams repeat success in the USA

Prague, 20 February 2012 - As many as 26 new trams may be delivered from the Czech Republic to the USA over the course of the next three years. Czech manufacturer, Inekon Group, entered into a contract with the City of Seattle, which undertook to purchase six vehicles and reserved an option on the purchase of twenty more. The value of the currently signed contract amounts to USD 26.6 mil. (i.e. nearly CZK 600 mil.). In the second half of this year, Inekon will commence production of the trams in the manufacturing plant of Ostrava Transport (Dopravní podnik Ostrava a.s.). The first completed tram is scheduled to arrive in Seattle at the beginning of 2014.

Seattle has placed an order for six vehicles

It involves the supply of 20 additional trams; Texas shows interest as well

Prague, 20 February 2012 - As many as 26 new trams may be delivered from the Czech Republic to the USA over the course of the next three years. Czech manufacturer, Inekon Group, entered into a contract with the City of Seattle, which undertook to purchase six vehicles and reserved an option on the purchase of twenty more. The value of the currently signed contract amounts to USD 26.6 mil. (i.e. nearly CZK 600 mil.). In the second half of this year, Inekon will commence production of the trams in the manufacturing plant of Ostrava Transport (Dopravní podnik Ostrava a.s.). The first completed tram is scheduled to arrive in Seattle at the beginning of 2014.

"Our first trams were delivered to Seattle in 2007. Since then, the trams have operated at a reliability rate reaching almost 100%. It was this reference, in particular, that seemed to be the main reason for our success in the tender proceedings held by the city last year," said Ing. Jan Hušek, PhD, Vice Chairman of the Board of Directors at Inekon Group, a.s. "*Seattle has the right to transfer the option on 20 more trams to a different customer. This customer would therefore not be required to organize a new tender. This opens up a whole world of opportunities in America. The City of Dallas in Texas has expressed its interest in the supply of three trams under this option,"* said J. Hušek.

Inekon Group repeated its success in Seattle with the same type of tram (Inekon 12-Trio). The USA model is low-floor, two-way vehicle including a lounge for passengers that is fully air-conditioned. The trams will be redesigned to cover a distance of approx. 0.75 km uphill without traction power supply. This will mark the first solution of its kind in the entire North America.

"The trams are generally equipped with a battery for safety reasons in case of power supply failures on the road. The battery, however, is capable of covering a maximum distance of 100 to 200 meters. Our designers now face the issue of a distance several times longer,

moreover uphill and including power supply for the air-conditioning system," explained J. Hušek.

The first tram will be completed in Ostrava. The citizens of this Moravian-Silesian city will have the opportunity to see the tram during its testing in the neighborhood of the Martinov´s manufacturing plant at the turn of 2013 and 2014.

For the next five vehicles, the final assembly will be provided for Inekon Group in Seattle directly by partner company Pacifica Marine. Bill Patz, CEO of Pacifica Marine, commented on the aforementioned as follows: "*We are happy about the contract signed with Inekon. We believe that this is merely the beginning which will allow us to supply new trams to Seattle followed by otherr American cities."*

The comments provided by representatives of the City of Seattle, who wish to use the trams on a new line titled First Hill Streetcar, are positive in the same manner. The line should connect the administrative centers of municipal district First Hill with main traffic routes in the remaining parts of the city.

"This investment into traffic infrastructure improvements will bring new labor opportunities and return money to our local economy. The extension to the rail traffic network will support the development of neighboring municipal districts and will offer citizens new transportation options. I congratulate Inekon and Pacifica on a job well done," said Mike McGinn, the Mayor of the City of Seattle.

Supplementary facts:

- INEKON trams are original Czech products. Vehicles are manufactured in cooperation with Ostrava Transport (Dopravní podnik Ostrava a.s.) in the central manufacturing plant in Martinov.
- The first three low-floor INEKON 12-Trio vehicles were launched with great anticipation on 12 December 2007. The biggest city of the state of Washington and the American northwest is not the only place where you can see these trams. At the turn of 2006 and 2007, three vehicles were delivered to Portland as well. INEKON GROUP delivered the first Czech trams to this big city in the state of Oregon as well as to Tacoma in the state of Washington as early as the end of the 1990s. Even the capital city of the USA, Washington D.C., purchased three new INEKON 12-Trio vehicles.
- The Pacifica Marine company specializes in the manufacturing and refurbishment of public transportation means. The company was established by the International Association of Machinists and Aerospace Workers with a mission to create new labor opportunities and creating new jobs in the state of Washington.

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Seattle tramway to be electrified in only one direction

08 November 2011

USA: The City of Seattle has selected Czech firm Inekon and its local assembly partner Pacifica Marine to supply six cars for a short tram line planned to connect First Hill with the future Capitol Hill light rail stop and the Chinatown/International District. The Inekon-Pacifica partnership was one of three bidders and will maintain the cars for five years.

The 3·2 km route is planned to open in late 2013. It replaces a plan for a light rail stop at First Hill which was dropped because of engineering, geological and construction risks.

The line will be double track, but overhead electrification will only be installed on the track towards First Hill. The return trip will powered by batteries, which as well as reducing energy consumption and maintenance costs will avoid interfering with trolleybus wires.

Inekon has previously supplied six trams to Seattle and has also won orders in Portland and Washington DC. Those were delivered fully built, but the Seattle cars must comply with Buy America regulations requiring 60% domestic content and US assembly.

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Seattle

First-Hill Streetcar Line

Began operation: Under Construction (Opens 2014)
Route Miles: 2.4
Stops: 10
Org: transit agency
Schedule: daily

The First-Hill project is the second line of Seattle's planned modern streetcar network. It entered the construction phase in April 2012, with operations scheduled to begin in early 2014. The 2.4 mile long line will connect the First Hill employment/ activity center (one of the city's largest employment centers, including the Seattle University campus and the Seattle Medical Center) to the regional transit system as well as intercity passenger rail; provide local transit service; accommodate economic development; and contribute to neighborhood vitality. Like the existing South Lake Union streetcar line, First Hill will be operated by King County Metro as part of the city's transit system. Because the two lines do not connect, a separate maintenance facility / operations base is being constructed. At 5th and Jackson, the new line will also pass the now mothballed Waterfront Streetcar alignment, although there are presently no plans to connect to it.

The double-track alignment is located entirely on city streets and utilizes a combination of center and side (blub-out) platforms for the 10 stops. For the Broadway leg of the alignment, the existing street is being extensively reconfigured, incorporating a two-lane bike path (dubbed the "Broadway Bikeway") along the east side, with the shared streetcar/ traffic lanes shifted towards the west curb. The project website has graphics illustrating the entire alignment, as well as video fly-overs (one of which is included below).

The line has several other unique aspects- it will negotiate long stretches of moderate grades, as well as short stretches of steep grades (up to 9%). Much of the alignment will also be shared with Metro's trolley bus system. Most unique is the fact that the line will take advantage of its prevailing grade, and the inbound track (which moves in the downhill direction) will not have overhead wire. The line's five vehicles (being supplied by Inekon, with final assembly in Seattle) will each be equipped with an onboard energy storage system that allows "off-wire" operation. This mode of operation facilitated keeping the trolley bus and streetcar overhead wire systems separate, and also simplified some of the project's interaction with other on-street and underground utilities. On an interesting historical note, sharing of overhead wire systems between trolley bus and streetcar was once common practice, albeit with trolley poles on the streetcar vehicles instead of pantographs.

Left- First-Hill Streetcar Map - click to enlarge
Middle- First-Hill in relation to South Lake Union Streetcar and Light Rail
Right- Broadway right-of-way illustration

Construction photos by Gordon Werner
News and Updates

8/29/12- Gordon Werner has a Flickr photostream with detailed photos of construction in progress.

Links

"Newest Streetcar to Remake First Hill", Seattle Times 4/11/12

Seattle Streetcar official website

Inekon Streetcar- Seattle page

ModernStreetcar.org website

This page was last updated on 8/29/12

Originally published April 10, 2012 at 9:24 PM | Page modified April 11, 2012 at 10:39 AM

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Newest streetcar to remake First Hill

Construction on the $134 million First Hill Streetcar line is to begin this month, with service expected to start in early 2014.

By Mike Lindblom
Seattle Times transportation reporter

PREV 1 of 2 NEXT

ELLEN M. BANNER / THE SEATTLE TIMES

Along Broadway on the east side (left side of street in the frame), there will be a 10-foot-wide, two-way bike lane.

RELATED
Streetcar work expected to bring more noise and disruption
Animation of the streetcar on its route
LA looks to revive mythic past with streetcars

First Hill Streetcar
THE 2 ½-MILE streetcar line is projected to:
Connect two light-rail stations: International District/Chinatown and Capitol Hill.

Open in early 2014.

Cost $134 million.

Create a mile of 10-foot-wide, two-way bike lane on Broadway separate from cars.

Reduce automobile and bus lanes from four to two lanes in places.

Cut street parking by 40 percent.

Information
See animation of the First Hill Streetcar line: http://seati.ms/IpmUGn

Streetcar on Broadway

W. STENSRUD / THE SEATTLE TIMES

Click to zoom | When the First Hill Streetcar opens in 2014, car traffic and streetcars will share one lane each direction on Broadway, with pockets of parking or turn lanes alongside, plus a continuous two-way bike lane. This image shows a northbound streetcar stopped near Seattle Central Community College, at Broadway and Pine Street.

First Hill streetcar

MARK NOWLIN / THE SEATTLE TIMES

Click to zoom and expand | Construction on the $134 million line is to begin this month, with service expected to start in early 2014.

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Before Seattle-area politicians knew better, Sound Transit promised voters in 1996 an underground station at First Hill, where riders could take an elevator

200 feet down to catch a regional light-rail train.

Then after studying the sliding soils on nearby Beacon Hill, transit officials realized that despite the value of putting a train stop in one of the city's biggest employment centers, it would be prohibitively expensive and risky to mine a deep vertical shaft among the high-rises of First Hill.

Sound Transit apologetically canceled the station in 2005 and in its place proposed a streetcar line to serve First Hill, without securing the money.

Now that voters have approved the funds — a near footnote in the $18 billion Sound Transit 2 plan of 2008, funded by higher sales taxes — construction on the $134 million streetcar line is to begin this month. Service is expected to start in early 2014.

There will be fewer lanes for car traffic and a loss of parking. On the other hand, the line will mean more-frequent transit, and a huge gain for bicyclists. Along much of the route, the streetcar will share a traffic lane with cars, as in many cities.

Despite its origins as a consolation prize, the 2 ½-mile project has become a magnet for great expectations, beyond just moving people through the state's most densely populated corridor.

The First Hill Streetcar, running mainly down Broadway, Yesler Way and South Jackson Street, is expected to:

- Attract more cyclists by creating a mile of bike lane, called a cycle track, separate from cars.

- Launch a homegrown train-building industry, when Pacifica Marine in South Seattle assembles six Czech-designed trains and tries to sign streetcar deals with other cities.

- Promote new technology using rechargeable batteries, not overhead wires, to power its southbound downhill trip.

- Preserve retail and tourist commerce in historic Pioneer Square, by going a few extra blocks west.

- Reach thousands of new housing units proposed in a rebuild of Yesler Terrace.

- Connect to a possible future streetcar downtown.

State's densest neighborhood

Can a project work this many miracles?

Its main purpose is to move people — ultimately 3,000 to 3,500 a day in a 2007 Sound Transit estimate, and the Seattle Department of Transportation has conjectured the count could go twice that high. By comparison, the South Lake Union streetcar carried 2,500 average weekday riders last month.

The route will connect two light-rail stations: the existing International District/ Chinatown Station and the Capitol Hill Station, to open in 2016. Near the line are Swedish, Harborview and Virginia Mason medical centers, Seattle Central Community College, Seattle University and O'Dea High School.

Skeptics argue that these places can be served by existing or enhanced bus lines, which are less expensive and can tackle steep hills directly to downtown.

Jack Whisner, a King County Metro planner speaking only for himself, suggested in a 2010 letter to Mayor Mike McGinn, that a new trolley-bus route be created on Yesler Way to Harborview.

Trolley-buses, powered by overhead electrical wires, are better for short hops and hill-climbing, while rail should be deployed for longer routes at quicker speeds, he argued in the letter, published in Seattle Met magazine.

"Right now, Seattle's just building short, slow, ineffective streetcar lines that are not providing much transit advantage," Whisner said in an interview last week. Supporters say the streetcar will serve a new north-south corridor that is underserved by buses, and will attract tourists.

"There will be people who ride a streetcar who won't ride a bus," says Michael Wells, executive director of the Capitol Hill Chamber of Commerce.

Some of them work at Swedish, where close to half the 7,000 employees drive to work. A streetcar will entice many out of their cars, said Sherry Williams, community-affairs director at Swedish.

She predicts that employees who live south of downtown will drop pricey First Hill garages, and instead find parking near a light-rail or Sounder station, hop the train, then transfer to the streetcar at King Street Station.

Bike-lane feature

The project's most novel feature is a 10-foot wide, two-way bike lane on Broadway, separated from cars by curbs and artistic bollards.

City-published animations underscore how this is a cycling project, as well as a transit project. Bicycles will often move faster than streetcars and motor vehicles. Seattle's policy of "complete streets" instructs the city to accommodate all modes of travel in road rebuilds.

Ethan Melone, streetcar project director for the Seattle Department of Transportation, says the bikeway is two feet wider than a pair of less safe 5-foot bike lanes that are often incorporated into road projects.

SDOT's efforts at bike-friendly design are partly a reaction to its early experience with the South Lake Union line, where bicyclists crashed by getting their tires stuck in the rails. Where bicyclists gain space, car drivers will lose some.

Street parking will be reduced 40 percent overall, said SDOT spokesman Rick Sheridan.

In several places, four car lanes of Broadway are being reduced to two lanes, for instance near Madison Street. Streetcars and automobiles will occupy the same lanes there, as well as on South Jackson Street, which will retain four lanes.

Streetcars are likely to get stuck in traffic, one reason the city predicts an 18-minute trip end to end. The city probably saved minutes by rejecting a route option on Boren Avenue, which, on many afternoons, is clogged by overflow traffic heading toward Interstate 5.

Streetcars and motorists alike could face delays where turning vehicles stop for cyclists and pedestrians at intersections, for instance near the community college.

But SDOT hopes to minimize the bottlenecks in other hot spots, such as Broadway to westbound James Street, with right-turn lanes that make room for drivers going straight.

Melone notes that very few passengers will ride the entire 18-minute length of the route — more likely they're going partway, from either of the two light-rail hubs.

Streetcars will arrive every 10 minutes, a frequency aimed at taking some edge off their slow pace.

Even backer Wells wonders how the mixture of sidewalks, bike tracks, parking spots, streetcars and automobiles will work: "Quite honestly, I'm still having a hard time seeing how all those will fit on the street."

In a short segment on 14th Avenue, trains will run behind Bailey Gatzert Elementary School, where parent Heather Ayres said the city needs to wage a huge, multilanguage safety campaign.

"It feels as though a very high-density traffic area is going to become more dense with traffic, unless they take certain measures," she said.

Another challenge, many years away, is a mixed-use redevelopment of Yesler Terrace, bringing eight-story buildings and up to 4,500 parking spaces, and related traffic, into an area already near saturation. On the other hand, thousands of newcomers would be next to a streetcar stop.

Aloha for streetcars

Backers say odds are improving for a $30 million extension a half-mile north to Aloha Street, so tracks can reach the entire Broadway small-business district, a few years after the initial line opens.

That's despite voter rejection of a car-tab fee last fall that included $18 million toward citywide streetcar design and possibly construction. The Federal Transit Administration shares the streetcar fervor of Seattle's elected officials, and even awarded $900,000 to plan a downtown line, alongside $2 million in Sound Transit funds to plan a Ballard line.

And a proposed federal rule change this year would increase the chances of small streetcar extensions to win FTA's multimillion-dollar construction grants — because, it is argued, streetcars can feed economic growth and add riders to a larger transit network.

Mike Lindblom: 206-515-5631 or mlindblom@seattletimes.com. On Twitter @mikelindblom.

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Monday, July 30, 2012

Siemens to supply catenary-free LRVs for Qatar Education City line

Written by **Keith Barrow**

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The Qatar Foundation has awarded Siemens a turnkey contract worth more than €100m to build and equip the 11.5km light rail line that will link Education City with the Doha Metro.

The contract includes signalling and communications systems, electrification, and depot equipment, as well as platform screen doors at four stations. Siemens also will supply a fleet of 19 Avenio low-floor LRVs, which will be equipped with the Sitras HES system for catenary-free operation.

Each roof-mounted Sitras HES module combines a double-layer capacitor with a NiMH battery, allowing the vehicle to store both traction and braking energy. Power converters transform the three-phase current with a rated voltage of 11kV into the 750V direct current required for charging the energy storage unit. The system will complete its charging cycle in just 20 seconds, taking power from charging points installed at each of the line's 25 stations, which will be fed by centralised rectifier substations.

The LRVs will also be adapted to operations in high temperatures, with a powerful air conditioning system and sun shades to protect roof-mounted electrical equipment from radiant heat. The 27.7m-long vehicles will feature a 2.55m-wide bodyshell and will accommodate up to 239 passengers.

The line will open in autumn 2015, and is a core part of the Qatar Foundation's plan to develop a car-free site at Education City.

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Supercapacitor light metro train unveiled

23 August 2012

CHINA: CSR Zhuzhou Electric Locomotive has unveiled a prototype light metro trainset which uses supercapacitor energy storage to operate without an external power supply.

Developed in conjunction with Chinese Academy of Engineering, the trainset has underfloor power pick-ups which are used to charge the roof-mounted supercapacitor unit from a fixed supply while the train is stood at a station. Charging takes 30 sec and can power the train for 2 km. Energy regenerated during braking is recovered for reuse.

The two-car articulated trainset which was rolled out on August 10 is designed for a maximum speed of 80 km/h, with an intended operating speed of 70 km/h. It is 2 650 mm wide, has a capacity of 320 passengers and is suitable for a minimum curve radius of 80 m.

The supercapacitor has a greater power density than lithium-ion batteries, and wireless operation is seen as a cheaper and less visually intrusive alternative to conventional electrification.

Commercial production is envisaged by 2014, with the manufacturer believing the technology could be viable for use in more than 100 smaller and medium-sized Chinese cities, as well as for the export market.

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Inside SWIMO, the Next-Generation Light Rail Vehicle

Rolling Smoothly with or without Overhead Wires

Electric trains are more energy efficient and generate fewer CO_2 emissions than other types of transportation systems. Next-generation light rail vehicles (LRVs) have been gaining momentum around the world, thanks to their low-floor design and low noise levels, as well as passenger- and earth-friendly features.

Kawasaki's SWIMO* is an LRV powered by the Gigacell®, Kawasaki's proprietary nickel metal-hydride battery, and can operate without overhead wires. The SWIMO test vehicle employs a three-carbody, three-bogie articulated design to enable smooth curving as well as flexibility in car combinations.

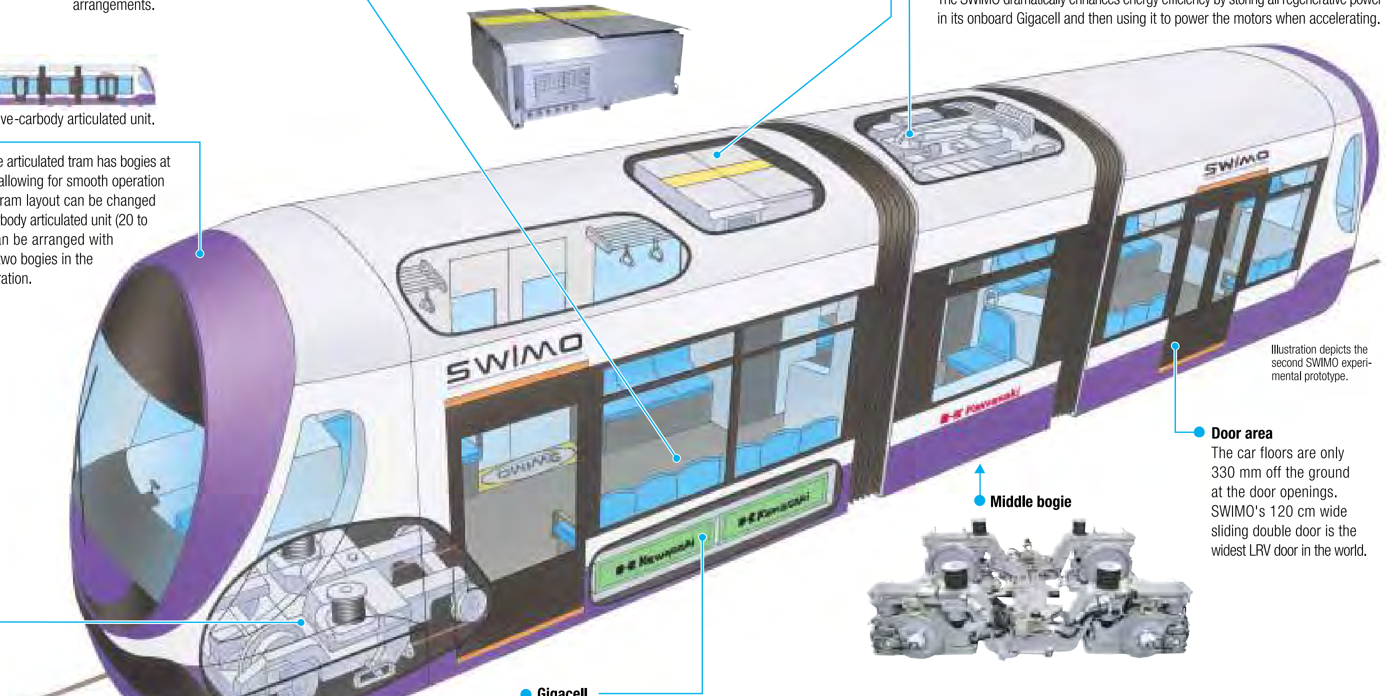
The 15 m long vehicle features floors that have been made as low as possible near the door. The aisle width is 800 mm at its narrowest section, allowing for ample wheelchair access. The SWIMO has 28 seats and can carry 62 passengers as standard capacity.

*SWIMO stands for "Smooth-WIn-Mover." It's the realization of Kawasaki's vision for a vehicle that would provide a smooth riding experience with a seamless transition to non-electrified sections, and a win-win green transportation solution via Kawasaki's innovative rail mover technology.

Testing at Kawasaki's Harima Works.

Trial run in Sapporo during winter.

Five-carbody articulated unit.



Car structure
The three-carbody, three-bogie articulated tram has bogies at both ends and in the middle, allowing for smooth operation even on narrow curves. The tram layout can be changed to any configuration. A five-carbody articulated unit (20 to 30 m class), for example, can be arranged with two bogies at both ends and two bogies in the middle, as shown in the illustration.

Passenger cabin
The floor height in the cabin sections is only 360 mm. The passenger cabins at both ends have completely flat floors, providing maximum flexibility in seating arrangements.

Roof Mounting major electric devices on the roof makes SWIMO's low-floor design possible.

Charge/discharge control system
The control system, developed by Kawasaki, ensures a steady supply of power from the battery and effective use of regenerative power while controlling fluctuations in power consumption from overhead wires. On non-electrified sections the control system provides a steady supply of power from the battery when the tram is accelerating and returns regenerative power to the battery for maximum efficiency.

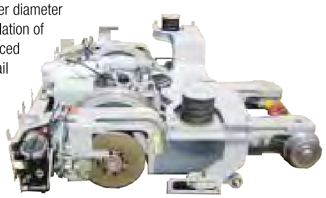
Braking system (regenerative brakes integrated with electronically controlled air brake system)
When braking, trains use their motor as a generator and return power to the overhead wires. This process, known as regenerative braking, is designed to enhance energy efficiency. Although power is returned to the overhead wires, transmission losses occur over long distances and if there are no other trains running nearby enough to use the regenerative power, it winds up being wasted. The SWIMO dramatically enhances energy efficiency by storing all regenerative power in its onboard Gigacell and then using it to power the motors when accelerating.

Illustration depicts the second SWIMO experimental prototype.

Door area
The car floors are only 330 mm off the ground at the door openings. SWIMO's 120 cm wide sliding double door is the widest LRV door in the world.

Middle bogie

Bogies at both ends
Kawasaki has developed compact bogies designed to fit under the driving cabs at both ends of the SWIMO in order to make the cabin floor flat. While this low-floor configuration would normally result in protruding wheels (conventional LRV wheels are generally 600 mm in diameter), the SWIMO circumvents this by reducing the size of the wheels on the second axle (the one farther from the operator's cab) to a diameter of 250 mm, as shown in the picture. The smaller diameter provides enough room for the flat-floor design and installation of doors over the wheels. The larger wheels have been placed under the operator's cabin along with the motor. While rail vehicles with wheels 360 mm in diameter or smaller have a history of derailing when switching tracks, Kawasaki has come up with a breakthrough development to keep SWIMO running safely on track. Kawasaki has conducted extensive testing on its state-of-the-art smaller wheeled bogie to ensure maximum safety.



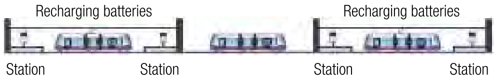
Gigacell
The Gigacell battery installed under the seats has been downsized for railway car applications and upgraded for larger output. The Gigacell is an extremely safe nickel metal-hydride battery tailored to large-scale applications. It employs a unique structure developed by Kawasaki which prevents the battery from generating excessive heat or igniting, even after quickly charging and recharging a large amount of power.

Charging time

The Gigacell can be charged in only three to five minutes after the SWIMO has traveled 10 km. That's the same amount of time it takes to turn the LRV around at a terminal.

Versatile operation
When operating in non-electrified sections, the SWIMO runs on its Gigacell batteries and returns regenerative power to the batteries when braking. Since the SWIMO is equipped with a pantograph, it charges the Gigacell while running on the power supplied from overhead wires in areas where they are available. There is no need for overhead wires when building new SWIMO lines or extending existing lines.

SWIMO blends in seamlessly with the cityscape
While overhead wires can mar the urban landscape, the SWIMO eliminates this concern and provides a more viable option for tourism planning.



KINKI SHARYO

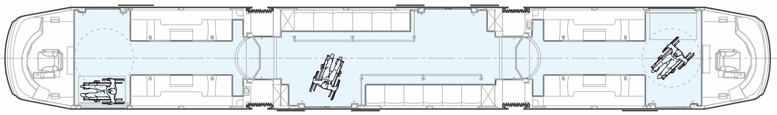
LFX-300

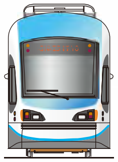
100% Low-Floor Hybrid Streetcar Powered by Li-ion Battery

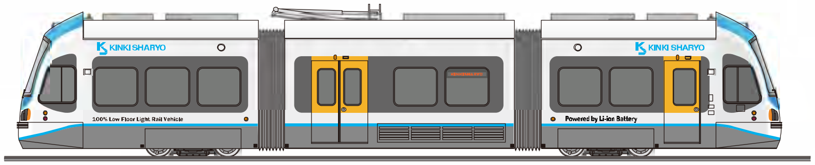
Vehicle Specification

Tare weight (AW0)		32 t (70.5 klbs)
Capacity		106 (seated 28)
Dimensions	Carbody length	20000mm (65ft 7.4in)
	Carbody width	2650mm (8ft 8.3in)
	Carbody height	3800mm (12ft 5.6in)
	Truck center distance	10800mm (37ft 5.6in)
	Minimum aisle width	880mm (2ft 10.6in)
	Floor height (TOR)	360mm (1ft 2.2in)
	Ceiling height	2400mm (7ft 10.4in)
	Clear door opening Double door:	1220mm (4ft)
	Single door:	815mm (2ft 8.1in)
Track & Operating conditions	Maximum steep slope	6 %
	Horizontal curve radius (min)	18m (59ft)
	Vertical curve radius (min)	350m (1148ft)
	Catenary voltage (nominal)	DC750V
	Operating voltage range	525～900V
	Maximum service speed	8 0 km/h (50 mph)
	Acceleration	3.5 km/h/s (2.2 mph/s)
	Deceleration Normal:	4.8 km/h/s (3 mph/s)
	Emergency:	6.0 km/h/s (3.7 mph/s)

Propulsion control		VVVF inverter control (IGBT) with regenerative and rheostanic brake
Auxiliary power supply		AC440V-60Hz,DC24V
Battery equipment		Li-ion rechargeable battery 40kWh
Trucks	Wheel	Resilient wheel
	Wheel base	1800 mm (5.9ft 70.8in)
	Gear ratio	44/7 = 6.29
	Brake system	Spring applied hydraulic brake Electrical regenerative brake Track brake
	Motor	120kw x4, 550V, 2370rpm (self-cooling type)







KINKI SHARYO

2-2-46 Inada-Uemachi
Higashi-Osaka City
Osaka Japan, 577-8511
PHONE: +81-6-6746-5240

400 Blue Hill Drive, Suite 3B
Westwood, MA 02090
PHONE: 1-888-4-SHARYO (474-2796)
EMAIL: BusinessDevelopment@kinkisharyo.com

www.kinkisharyo.co.jp

LFX-300

100% Low-Floor Streetcar with Wireless Battery Power Propulsion System, the LFX-300 is user-friendly and environmentally responsible.

KINKI SHARYO

1

Wireless Hybrid System: Energy-Saving & Eco-Friendly

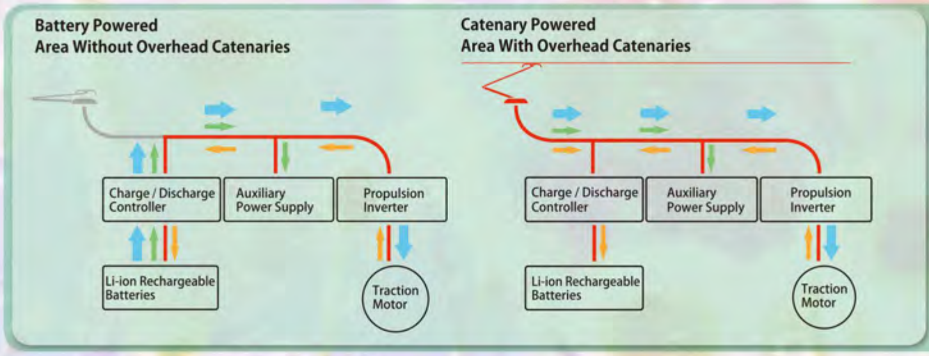
The LFX-300 operates using standard catenary electric power to recharge a set of Li-ion batteries. In a wireless operating segment, LFX-300 is powered by the batteries, which are then rapidly recharged when operating on catenary power and by regenerative braking.

Benefits: Downtown and historic landscapes remain beautiful and uncluttered by overhead catenary wires; vital in areas with aesthetic or historic preservation requirements. Clearances for overpasses, viaducts and city events are no longer hindered by overhead catenary wires. In addition, system developers can realize cost reductions by reducing wayside traction power equipment and maintenance.

2

Designed for Customer's Needs

Designed from the ground up for compliance with ADA, Buy America, and NFPA-130 requirements, the LFX-300 will set a new standard for downtown surface rail operations with wireless battery power propulsion. LFX-300's 100% Low-Floor configuration will maximize passenger loading and unloading allowing for higher frequency of operations. The whole floor is one level to allow all passengers (including wheelchairs, baby strollers, disabled, senior citizens and children) the ability to maneuver easily within the vehicle. Providing for level boarding without steps, the advanced Hydraulic Suspension System swiftly responds and adapts to floor height variations due to passenger load changes. The floor and platform always remain flush allowing passengers to board or exit swiftly and safely.



Battery Powered
Area Without Overhead Catenaries

Charge / Discharge Controller
Auxiliary Power Supply
Propulsion Inverter
Li-ion Rechargeable Batteries
Traction Motor

Catenary Powered
Area With Overhead Catenaries

Charge / Discharge Controller
Auxiliary Power Supply
Propulsion Inverter
Li-ion Rechargeable Batteries
Traction Motor

Eco-Friendly Sustainable Design

Meeting the highest standards for efficiency and quality, the LFX-300 offers safe zero emissions transportation and is built using materials and processes consistent with the latest international environmental standards.

ameriTRAM™

The 100% Low-Floor Streetcar Engineered for North America

KINKISHARYO
Engineering Sustainable Urban Transit

www.ameritram.com

ameriTRAM™

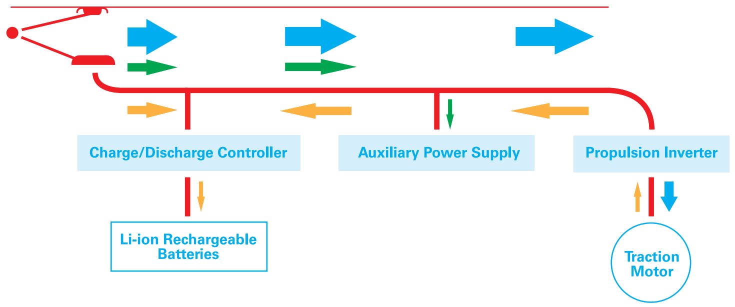
North America's 100% Low-Floor Streetcar

e-Brid™

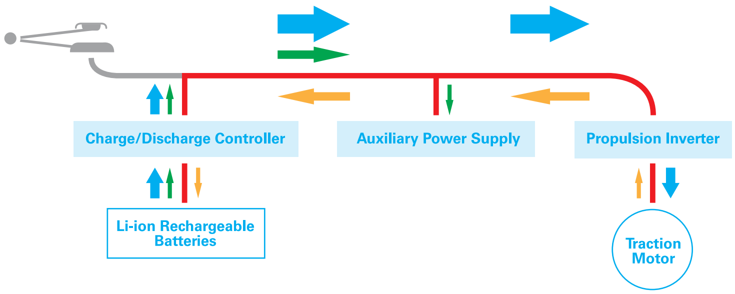
Electro-Hybrid Li-ion Battery Power Propulsion Technology

Through unique e-Brid ™ technology, *ameriTRAM* ™ is propelled by overhead catenary or on-board lithium-ion batteries. e-Brid ™ charges the batteries while running on catenary power; and, when in battery mode, uses electricity stored from regenerative braking.

Powered by Catenary



Powered by Li-ion Batteries



Through e-Brid™ technology *ameriTRAM™* provides:

+ **Superior Versatility**
  Achieve propulsion where overhead contact wire cannot be installed

+ **Historic Preservation**
  Free downtown and historic areas of overhead wires

+ **Improved Aesthetics**
  Minimize environmental impact and improve visual aesthetics through wireless sections

+ **Reduced Energy Usage**
  Realize immediate savings though lower power consumption via "peak-shaving"

+ **Greater Value**
  Save millions in capital investment and operational costs with less electrification equipment and maintenance

+ **Enhanced Public Safety**
  Ensure safety of passengers in power outages or inclement weather

+ **Environmental Responsibility**
  Realize fewer greenhouse gas concerns through zero emissions and lower energy usage

Engineered For North America

ameriTRAM™ is the only streetcar in North America that is compliant with ADA, Buy America, NFPA-130 and ASME RT-1

100% Low-Floor

With its 100% Low-Floor, *ameriTRAM*™ offers:

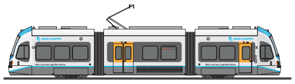
+ **Improved Passenger Safety**
  100% low-floor with no interior steps or ramps

+ **Superior Access**
  ameriTRAM™ provides easier access and complies with all ADA requirements throughout the passenger area

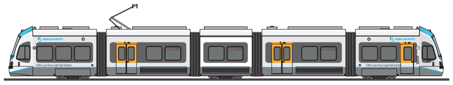
+ **Greater Efficiency**
  Faster boarding means less dwell time at stations

Flexible Modularity

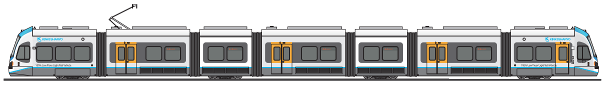
Expandable design allows for future system growth without increasing fleet size



ameriTRAM™ 300



ameriTRAM™ 500



ameriTRAM™ 700

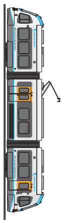
KINKISHARYO International, L.L.C. is the #1 supplier of low-floor light rail vehicles in North America.

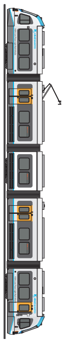
With the introduction of *ameriTRAM*™, Kinkisharyo is the only light rail manufacturer to supply North America with a 100% low-floor, electro-hybrid, zero-emission streetcar powered by either overhead electric catenary or on-board lithium-ion batteries. Headquartered in Westwood, MA, KINKISHARYO has been redefining urban light rail transit systems throughout the U.S. for nearly three decades.

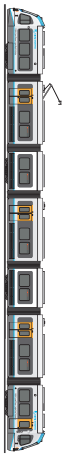
For more information on *ameriTRAM*™
www.ameritram.com

Vehicle Specification

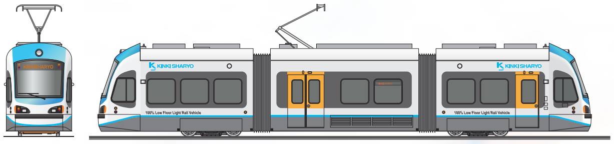
***ameri*TRAM**™		**300**	**500**	**700**
	Empty Weight with e-Brid ™	**32 mt** (70.5 klbs)	**48 mt** (105.5 klbs)	**64 mt** (141 klbs)
	Passengers (4/m2)	**115** (28 seats)	**150** (62 seats)	**190** (96 seats)
Primary Dimensions	Length over Anticlimbers	**20m** (65 ft 7.4 in)	**30m** (98 ft 5 in)	**40m** (131ft 2.8 in)
	Width of Carbody *	**2.65m/2.46m** (8 ft 8.3 in/8 ft 1 in)		
	Width of Thresholds *	**2.71m/2.52m** (8 ft 10.7 in/8 ft 3.2 in)		
	Height of Carbody	**3.8m** (12 ft 5.6 in)		
	Boarding Height	**350mm** (13.75 in)		
	Ceiling Height	**2472mm** (8 ft. 1.3 in.)		
	Clear door opening Double Door: Single Door:	**1220mm** (4 ft.) **815mm** (2 ft. 8.1 in.)		
Trucks	Truck Centers	**10.8m** (35 ft. 5.2 in.)		
	Wheel Diameter	**600mm** (23.6 in.)		
	Wheel Base	**1800mm** (70.9 in.)		
Operating Parameters	Maximum Grade **	**9%**		
	Minimum Horizontal Curve	**18m** (60 ft.)		
	Minimum Vertical Curve (+/-)	**350mm** (1150 ft.)		
	OCS Voltage (DC)	**750 nominal** (525-900 range)		
Performance	Maximum Service Speed	**80 kph** (50 mph)		
	Acceleration **	**1.3m/s^2** (3.0 mphps)		
	Service Brake	**1.3m/s^2** (3.0 mphps)		
	Emergency Brake	**2.3m/s^2** (4.5 mphps)		
Primary Sysystems	Propulsion	**IGBT Inverter with VVVF Controls**		
	Friction Brake	**Hydraulic Disc**		
	Auxilary Power	**208vAC - 3phase - 60hz**		
	LVPS	**24vDC**		



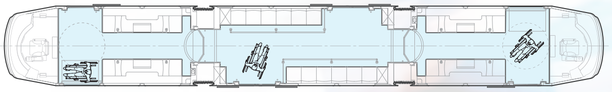




*Available in wide (LRV) or narrow (Streetcar) versions
**All axles powered



***ameri*TRAM**™ Streetcar, exterior



***ameri*TRAM**™ Streetcar, interior

KINKISHARYO International, LLC
US Headquarters:

400 Blue Hill Drive, Suite 3B
Westwood, MA 02090

T. 1-888-4-SHARYO (474-2796)
E. businessdevelopment@kinkisharyo.com

For more information please visit
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Genève tram trial assesses supercapacitor performance

07 August 2012

SWITZERLAND: Genève tram operator TPG is testing a prototype supercapacitor energy storage unit which allows braking energy to be recovered, and enables a tram to run for short distances without an external power supply.

The 1 tonne supercapacitor unit has been installed on the roof of one of a batch of 32 Tango trams being delivered to TPG by Stadler Rail. It can store the equivalent of the entire kinetic energy of an empty tram moving at 55 km/h, according to Stadler, and is more effective than batteries at absorbing and releasing the high short-term currents produced during braking.

Energy regenerated during braking is reused as the vehicle starts to move, when its power requirement is highest. The stored energy can also power the tram for at least 400 m if the overhead supply should fail. A distance of 1500 m has been achieved with careful driving under low-acceleration, low-speed test conditions.

The prototype is undergoing extensive testing by TPG, Stadler and traction equipment supplier ABB. Its energy consumption is being compared with the rest of the Tango fleet equipped for conventional regenerative braking which feeds current back into the overhead supply.

If the tests prove successful, the other 31 Tango vehicles for TPG could be equipped with supercapacitors 'relatively easily'.

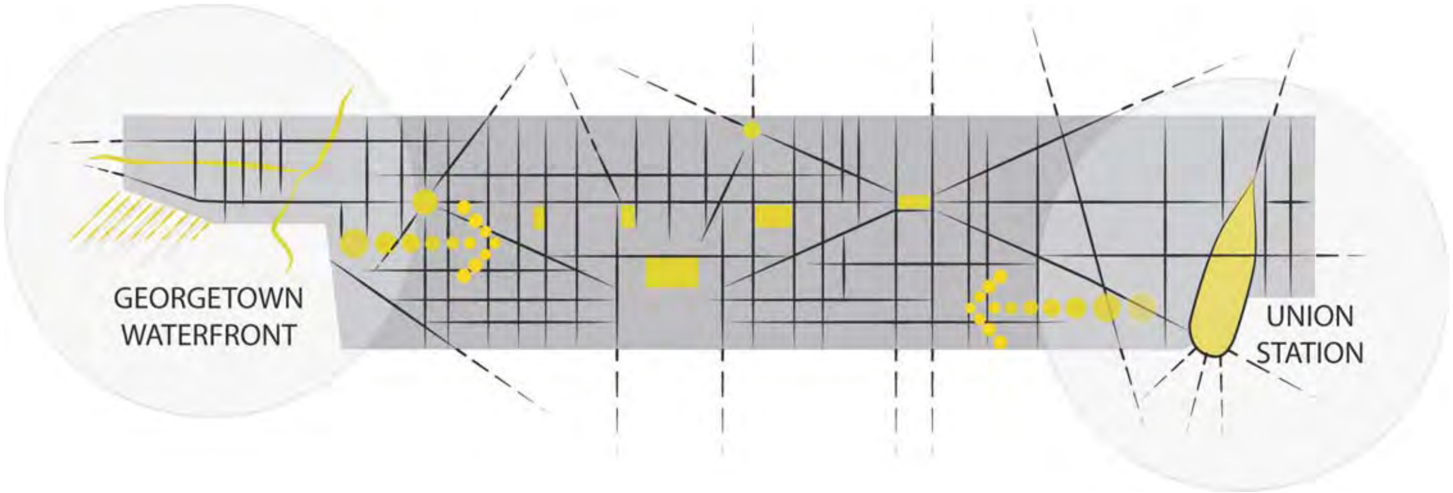
Related News:

- Alstom to test onboard flywheel energy storage - 18.01.13
- European Commission backs regenerative braking R&D - 04.12.12
- Supercapacitor light metro train unveiled - 23.08.12
- Supercapacitor energy storage for South Island Line - 03.08.12
- Zaragoza tram Line 1 enters service - 26.04.11
- Rhein-Neckar Verkehr orders more supercapacitor trams - 05.04.11
- Genève chooses the Tango - 26.01.10
- Supercapacitors to be tested on Paris STEEM tram - 08.07.09
- Ultracapacitors on test - 08.01.09
- SuperCap tests complete - 18.03.08
- Wayside and on-board storage can capture more regenerated energy - 02.07.07
- Double-layer capacitors store surplus braking energy - 01.11.01

Alternatives Analysis for Premium Transit Service
from Union Station to Georgetown

APPENDIX B

Technical / Informative Sessions with Car Builders



SIEMENS

DC Streetcar Options for ESS

Richard Palmieri
Siemens Rail Systems – Regional Sales Director

Peter Tuschinski
Siemens Rail Systems - Strategy North America

Washington DC
April 3 2013

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SIEMENS

Agenda

Confirm status of Streetcar Project DC
  - Planning and timeline
  - Status alignment
  - Vehicles and options
  - Critical Success Factors

Siemens S70 Streetcar
  - Technology

Energy Storage for LRVs
  - Baseline – options and technology
  - Siemens References
  - Energy Storage ‘made for the US’

SIEMENS

DC Streetcar Status

H Street / Benning and Anacostia Segments

- In construction with opening planned in 2014
- 2.75 miles
- Three Inekon T12 Streetcars
- Three additional Skoda T10 Streetcars on order
- Conventional overhead power

22 Mile Streetcar DBOMF

- Industry RFIs received
- Next action in segments or as P3?
- Requirements for off-wire operation – L'Enfant Plan

Georgetown Alternative Analysis

- Process and timeline discussion

SIEMENS

Agenda

Confirm status of Streetcar Project DC
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Siemens S70 Streetcar Technology
  Specifications

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- Baseline – options and technology
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SIEMENS

Siemens S70 Streetcar

Performance and Capacity

Maximum operational speed
35 mph
56 km/h

Passenger capacity:
60 seats
Approx. 195 total passengers @ 6 p/m²
4 wheelchair spaces

Catenary supply voltage:
750 Vdc

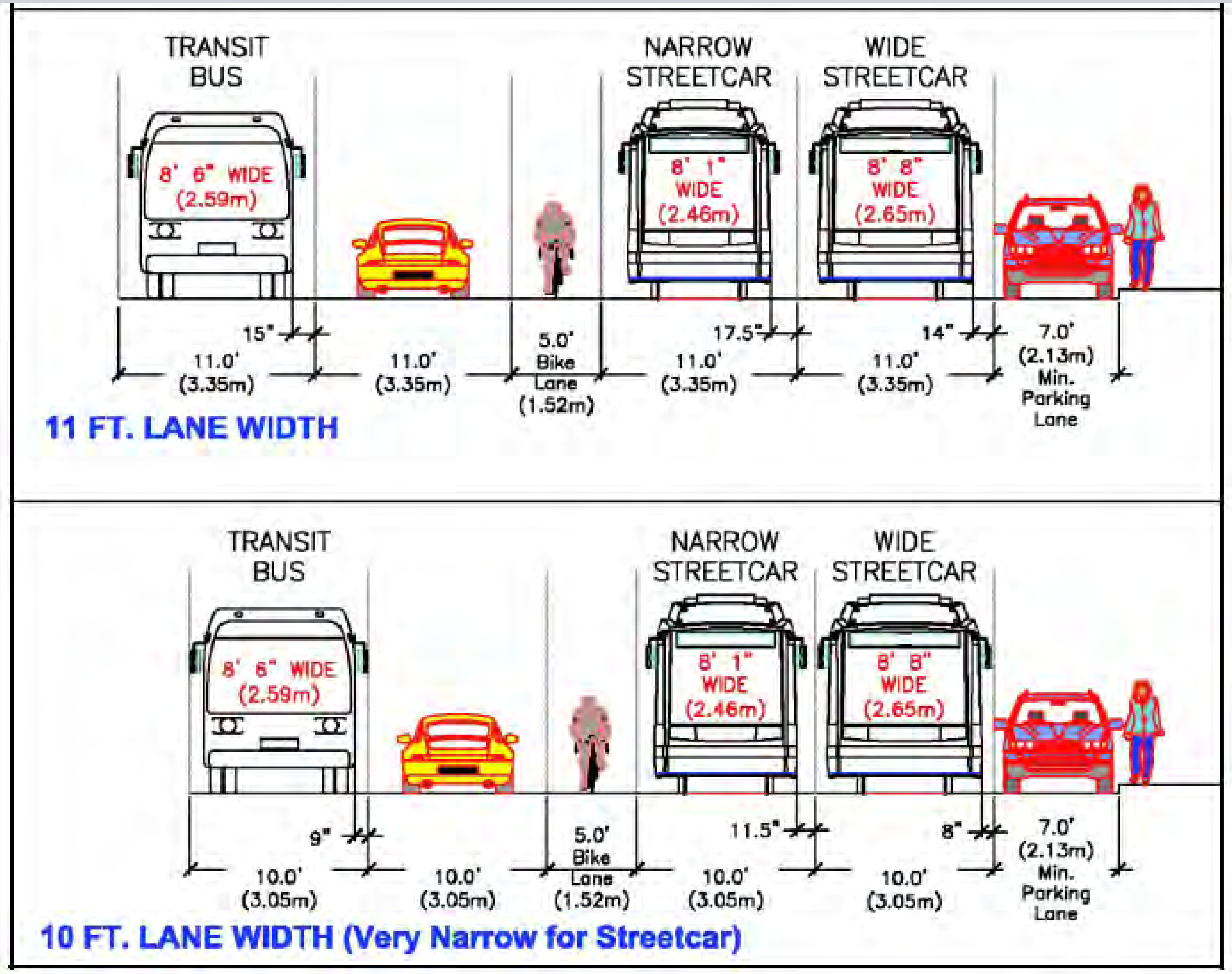
Length over anticlimbers:
79.1 ft
24110 mm

Width:
8.7 ft
2654 mm

Vehicle empty weight:
96,500 lbs (AW0)
43700 kg

Siemens S70 Streetcar
Urban Fit and Lane Width

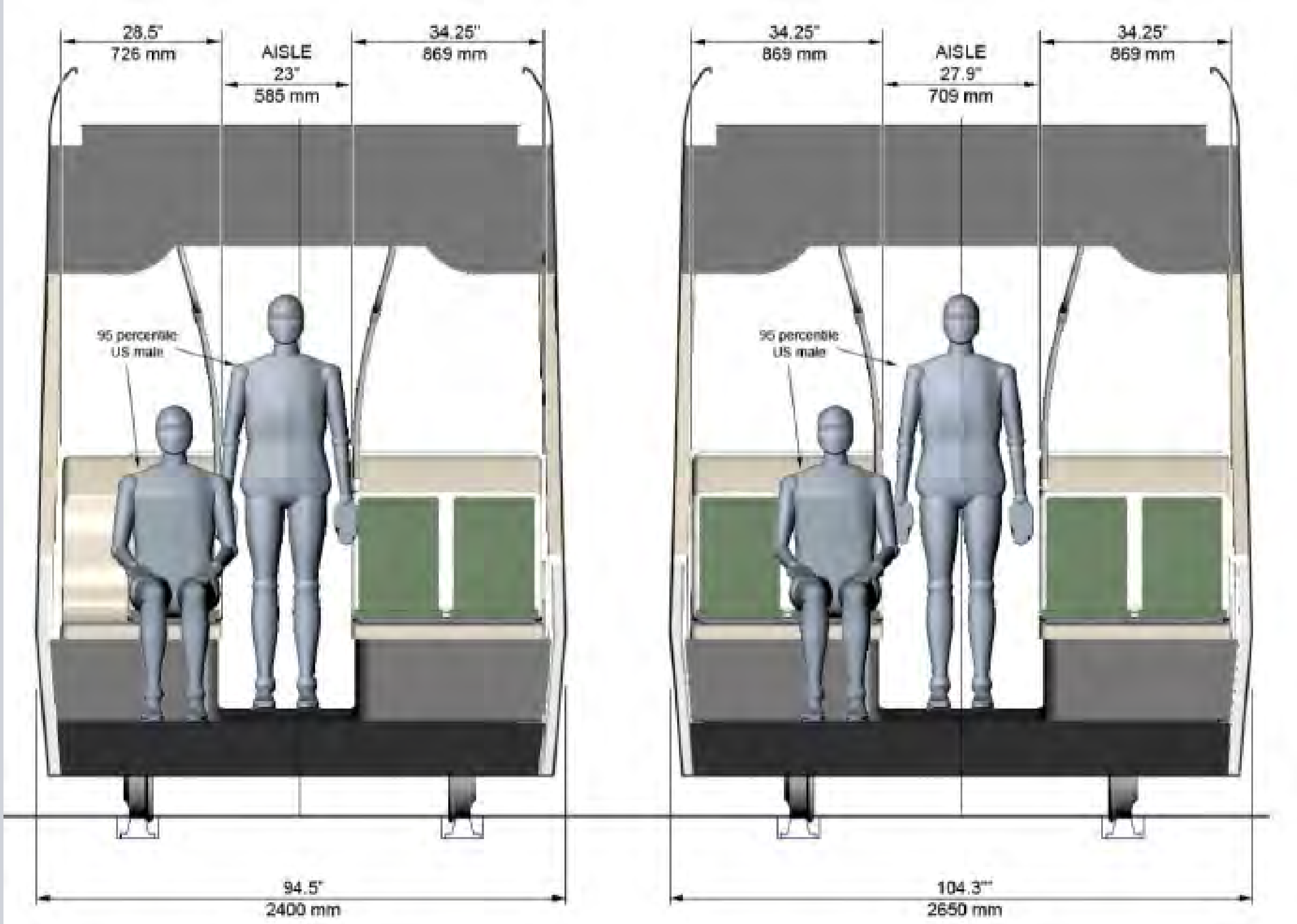
SIEMENS



Source: APTA Modern Streetcar Vehicle Guidelines

Siemens S70 Streetcar
Vehicle Width and Passenger Comfort

SIEMENS



Source: APTA Modern Streetcar Vehicle Guidelines

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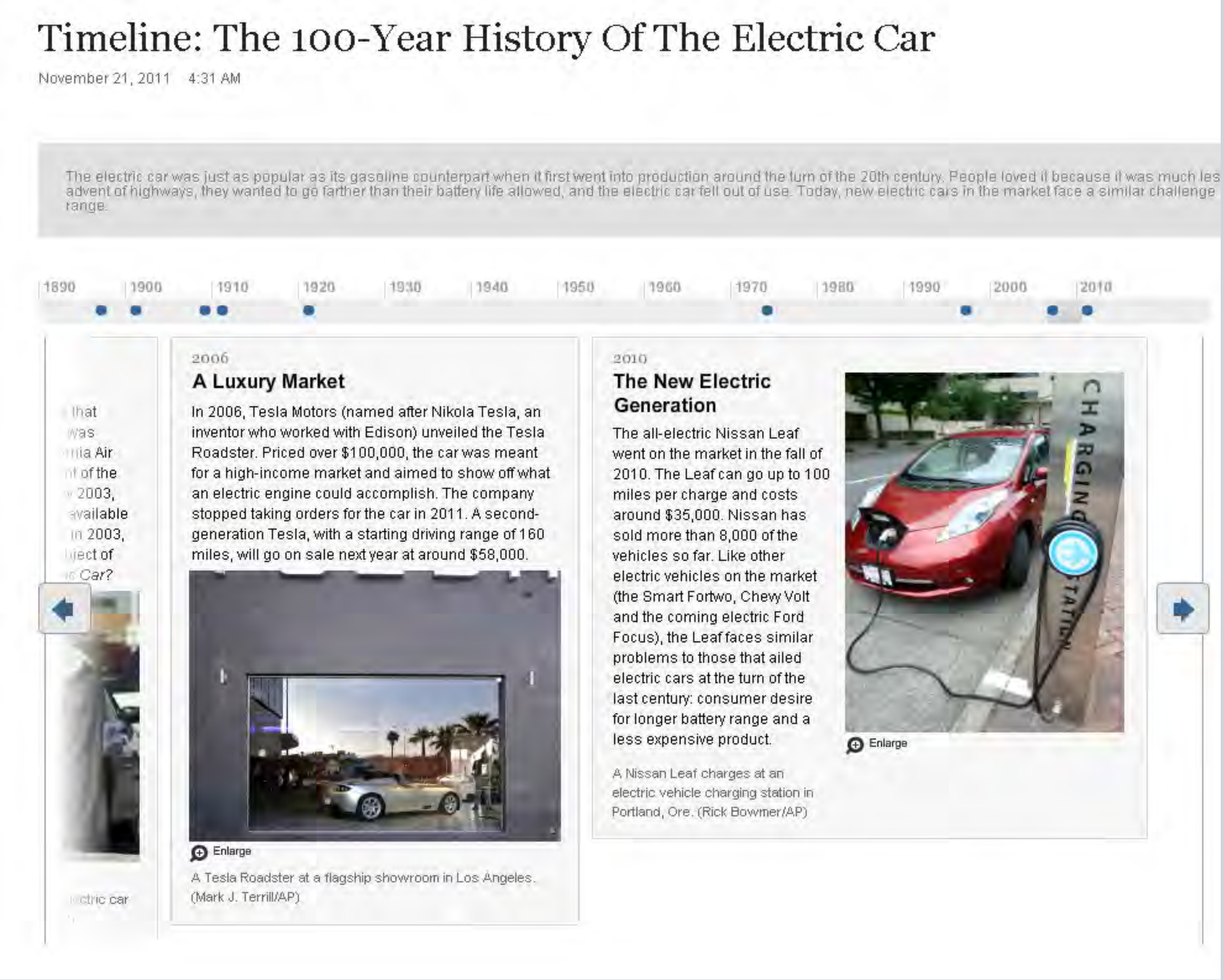
Electric cars
Recent breakthroughs leading to mass availability

SIEMENS



Timeline: The 100-Year History Of The Electric Car

November 21, 2011 4:31 AM

The electric car was just as popular as its gasoline counterpart when it first went into production around the turn of the 20th century. People loved it because it was much les
advent of highways, they wanted to go farther than their battery life allowed, and the electric car fell out of use. Today, new electric cars in the market face a similar challenge
range.

that
was
nia Air
of the
2003,
available
in 2003,
ject of
Car?

ctric car

2006

A Luxury Market

In 2006, Tesla Motors (named after Nikola Tesla, an inventor who worked with Edison) unveiled the Tesla Roadster. Priced over $100,000, the car was meant for a high-income market and aimed to show off what an electric engine could accomplish. The company stopped taking orders for the car in 2011. A second-generation Tesla, with a starting driving range of 160 miles, will go on sale next year at around $58,000.

A Tesla Roadster at a flagship showroom in Los Angeles. (Mark J. Terrill/AP)

2010

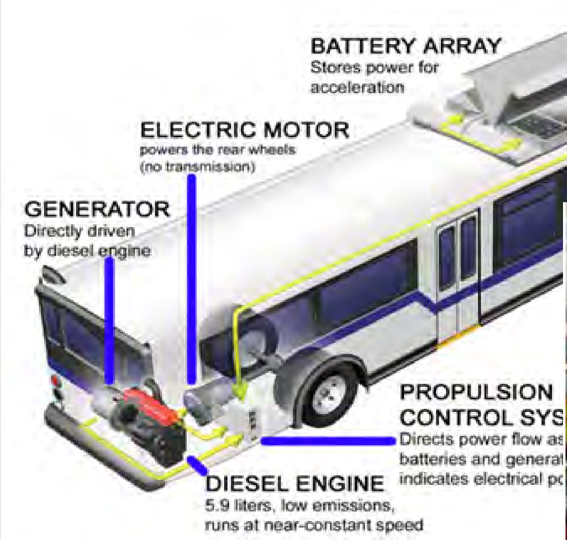
The New Electric Generation

The all-electric Nissan Leaf went on the market in the fall of 2010. The Leaf can go up to 100 miles per charge and costs around $35,000. Nissan has sold more than 8,000 of the vehicles so far. Like other electric vehicles on the market (the Smart Fortwo, Chevy Volt and the coming electric Ford Focus), the Leaf faces similar problems to those that ailed electric cars at the turn of the last century: consumer desire for longer battery range and a less expensive product.

A Nissan Leaf charges at an electric vehicle charging station in Portland, Ore. (Rick Bowmer/AP)

Source : NPR.com

Transit : Hybrid Buses
Combining Diesel with electric propulsion


BATTERY ARRAY
Stores power for acceleration
ELECTRIC MOTOR
powers the rear wheels (no transmission)
GENERATOR
Directly driven by diesel engine
PROPULSION CONTROL SYS
Directs power flow as
batteries and generat
indicates electrical pc
DIESEL ENGINE
5.9 liters, low emissions, runs at near-constant speed

Environmental

Innovation

Economic

SIEMENS

Key benefits of mobile Energy Storage Systems

Regenerative braking with ESS:

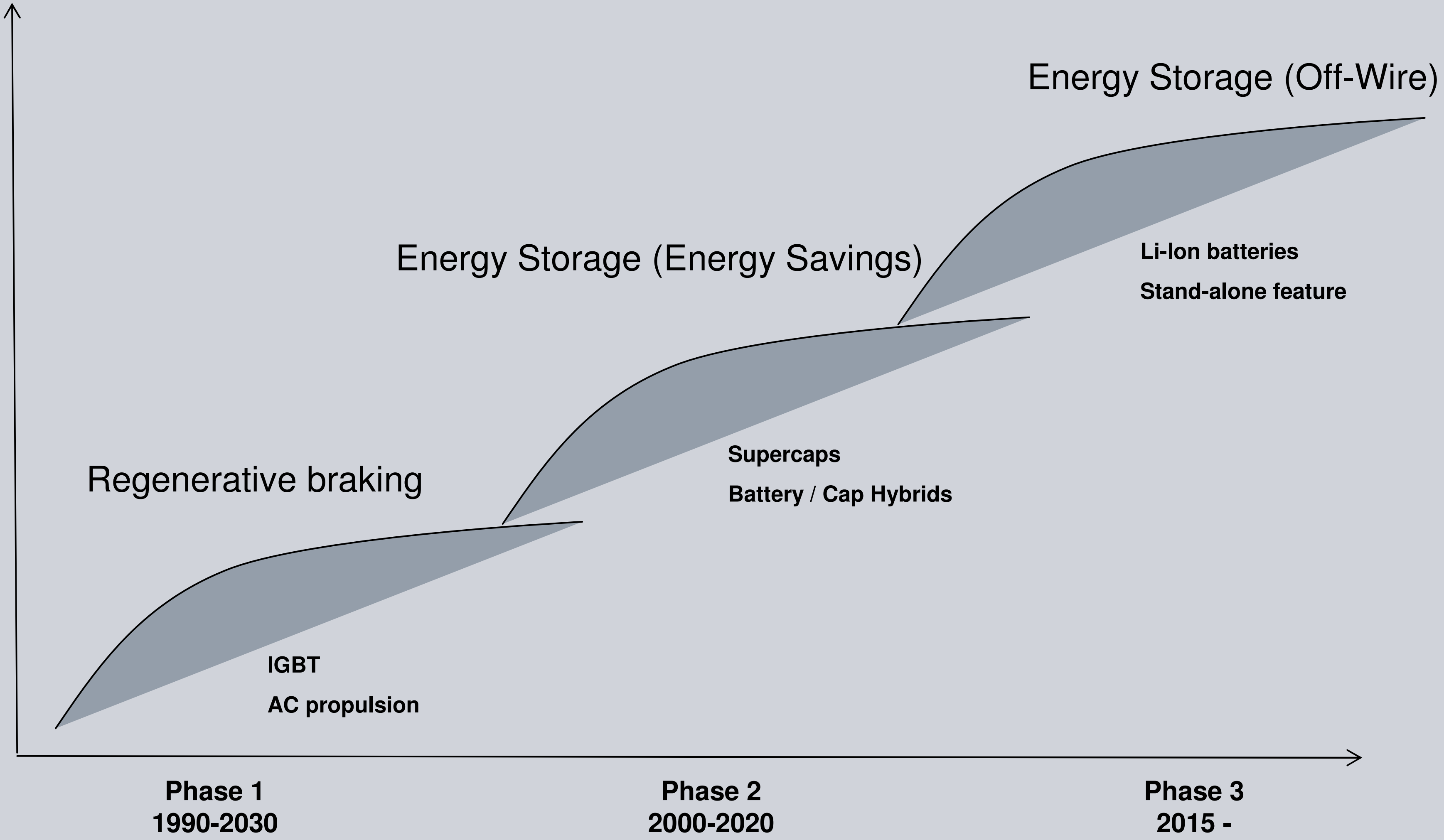
- Energy savings up to 30%
- Reduction of operating cost
- Reduction of CO_2 emissions
- Reduce use of expensive peak loads

Off-wire operating mode

- Short sections w/o need for electrification, i.e:
  - Tunnels or bridges
  - Intersections
- Aesthetic improvement in visually sensitive or historic neighborhoods

Electric Rail Vehicles: Energy SAVING Systems
Major Development Phases

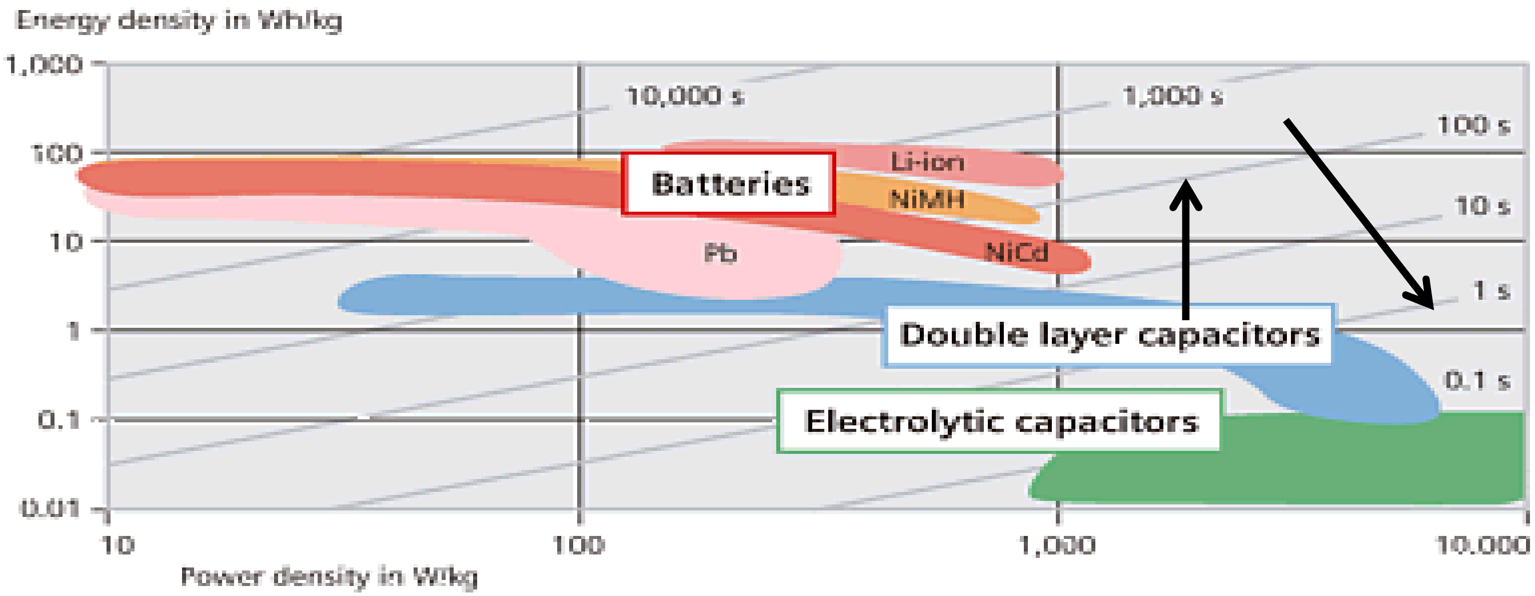
SIEMENS



Batteries and Capacitors
Key technologies as enablers – view from 2007

SIEMENS

Comparison of Battery Systems



Battery type	Energy density Wh/kg	Power density W/kg	Service life in cycles / years
Lead-acid battery	30 – 50	150 – 300	300 –1,000 / 3 – 5
Nickel-metal hydride battery	60 – 80	200 – 300	>1,000 / >5
Lithium-ion battery	90 – 150	500 – >2,000	>2,000 / 5 – 10
Supercaps (double layer capac.)	3 – 5	2,000 – 10,000	1,000,000 / unlimited

Availability and proven technology of storage modes for ESS

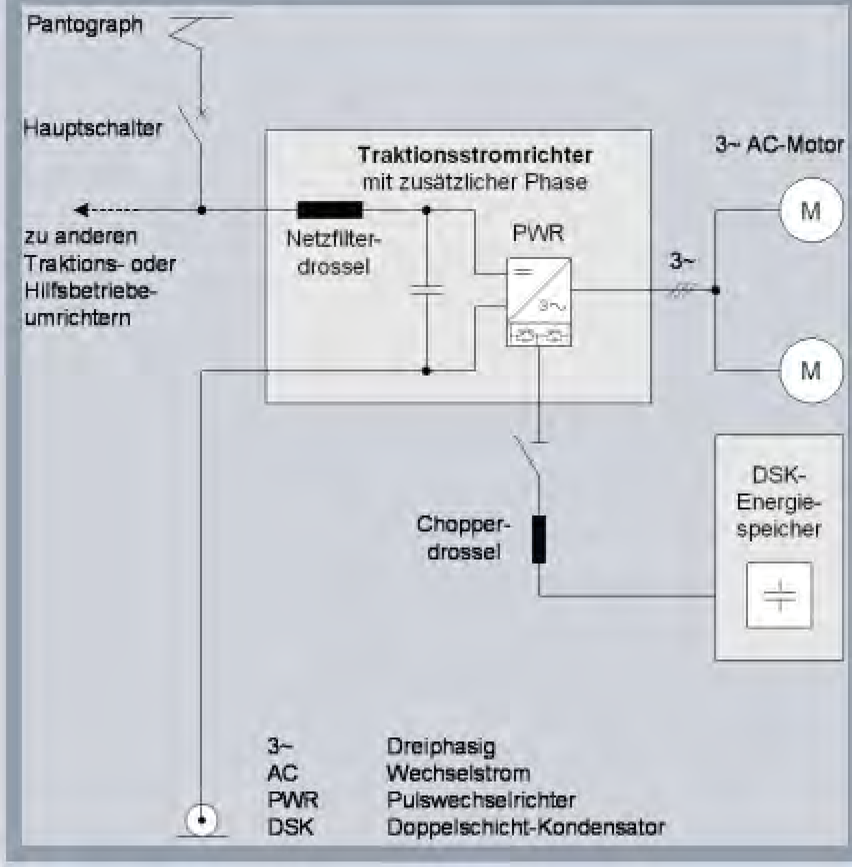
	Savings	Off-Wire	Tested	Cost
Supercaps	●●	○	●●	●
NiMH *(or other classic batteries)*	◖	◖	●	○
Hybrid	●●	●	●●	○○
Li Ion (assumed)	●●	●●	◖	●
Others *(off-wire only)*	?	●●	?	?

New development : Li Ion batteries for use in LRVs

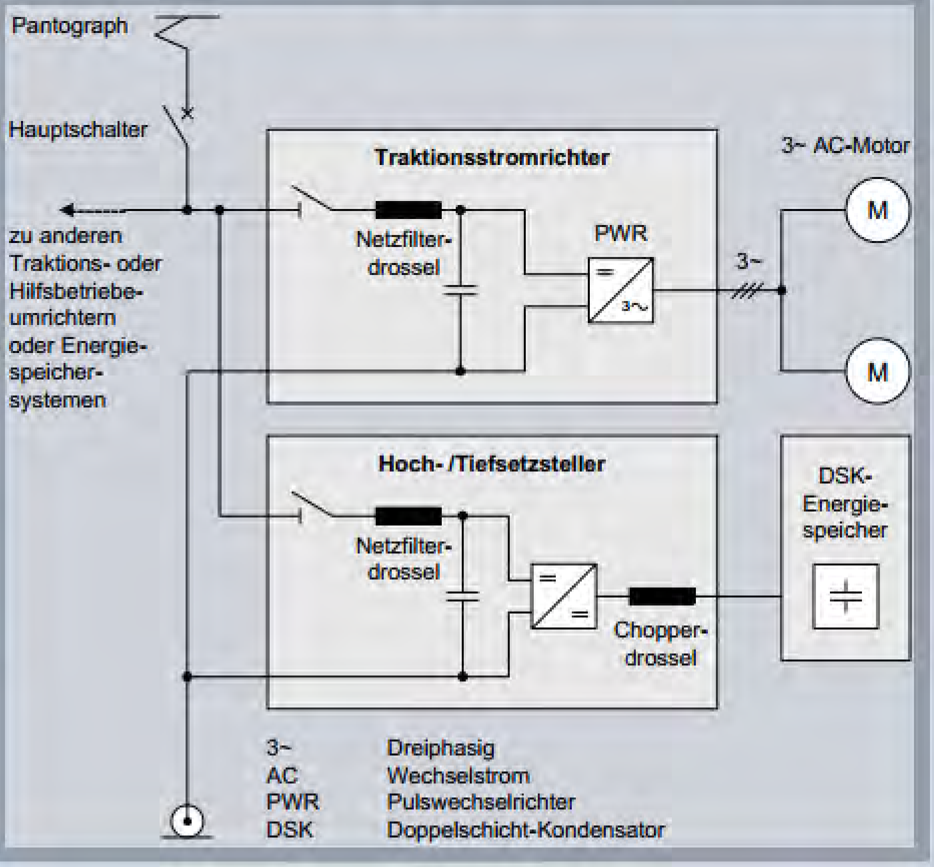
- Demand through consumer goods, diesel hybrids and EVs
- Federal funding and recognition as green energy
- New chemistries

High Level options for integration of ESS

High Integration ESS



Low Integration ESS



Agenda

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Siemens S70 Streetcar

- Technology

Energy Storage for LRVs

- Baseline – options and technology
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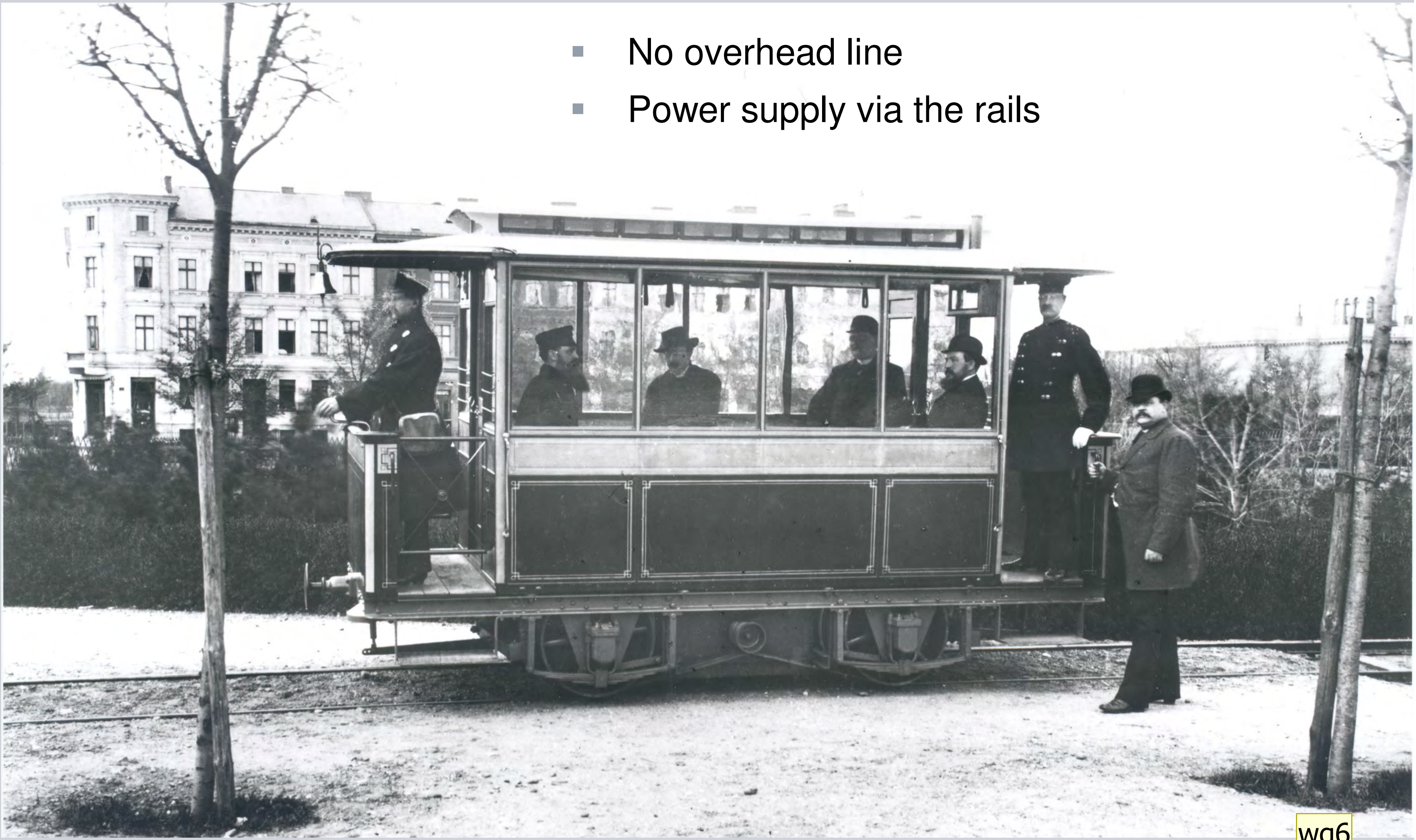
- Energy Storage ‘made for the US’

Berlin Lichterfelde 1881
The world's first electric tram

SIEMENS



- No overhead line
- Power supply via the rails

Slide 18

---

wg6 Fußzeile bitte nicht überdecken.
e09gunw0, 9/17/2012

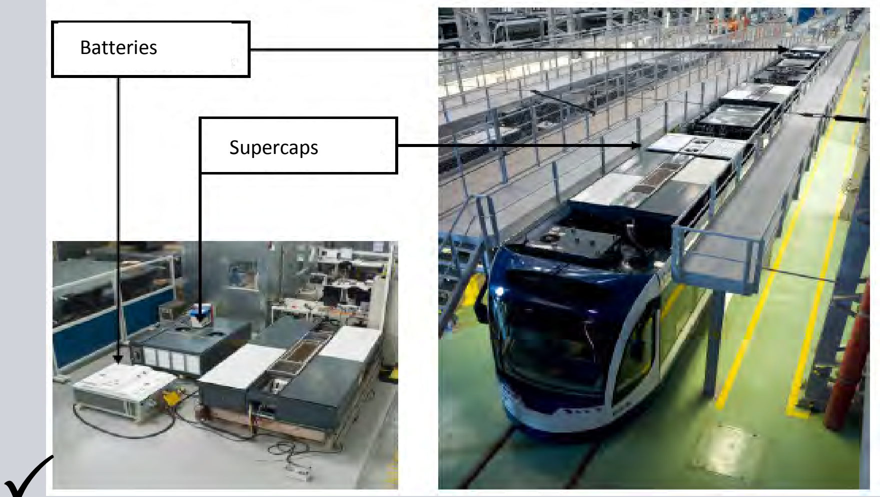
Hybrid ESS
Lisbon, Portugal

SIEMENS

Customer:	Metro Sul do Tejo, Almada, Portugal
Vehicle:	Combino Plus (2008)
Project:	24 100% low-floor , four-section trams
ESS:	Hybrid system (Caps and NiMH battery) Prototype with 2.8kWh energy content

Key benefits provided:

- Energy savings of more than 10%
- Reduced peak-demand
- Up to 1.5 miles of off-wire operation
- Availability >99.8%



Validated the engineering modeling assumptions ✓

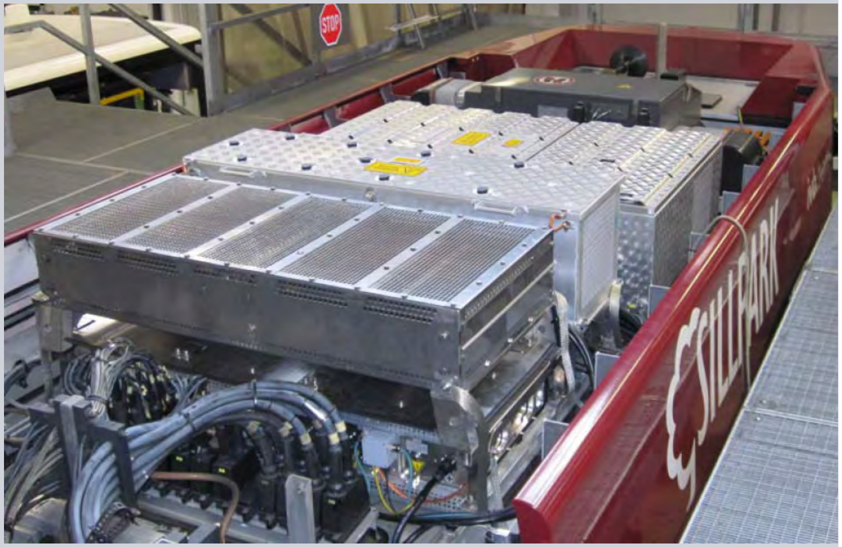
Integrated Capacitor ESS
Innsbruck , Austria

SIEMENS

Customer: Innsbruck, Austria

Project: 32x ELIN EBG propulsion system (2010)

ESS: Capacitor based prototype with 0.4kWh
Highly integrated focus on Energy Savings



Key benefits provided:

- Energy savings of more than 10%
- Reduced peak-demand
- Reduced voltage drop along the overhead contact line
- Stabilized traction power supply

Validated the engineering modeling assumptions ✓

Qatar Education City 2015
The world’s first completely catenary free tram system

SIEMENS

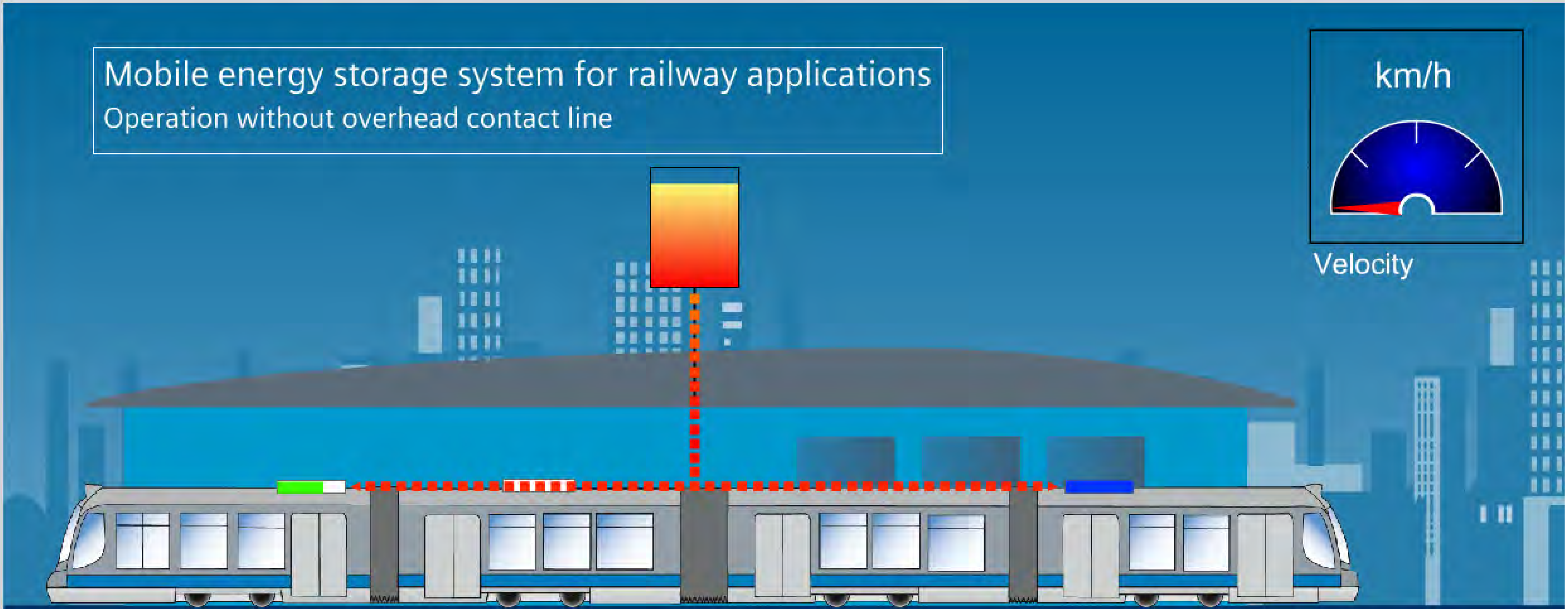
Education City: new university campus in Doha, Qatar, for 10,000 students.

Link of university facilities, cultural places and residential areas on the campus:

- 11.5 km of track
- 25 stations
- 19 Avenio trams
- Innovative NVC system (Non-Visible Contact line) avoiding catenary
- Siemens supplies complete turnkey tram system (except for civil works)

How is the Siemens Catenary Free Solution working?

SIEMENS


Mobile energy storage system for railway applications
Operation without overhead contact line
km/h
Velocity

Phase 1

Vehicle is stopping at a station with a charging unit.
Energy flows from the charging unit to complete the charge of the mobile energy storage.

SIEMENS

Key considerations for ESS

Sizing of an energy storage system (ESS)

- Targeted for off-wire duties is X
  → Sizing for ESS for more than X
- Mitigate possible interference in operation
  → thus over sizing the ESS
- Factor: separation of right-of-way.

Separation ↑ Interference ↓ ESS sizing ↓

Real-life project specific energy savings will vary :

- 30% entirely possible
- Vehicles are operated in a network of other vehicles and alignments.
- Modern vehicles all have the ability to regenerative braking

Network complexity , size ↑ Potential for Energy Savings ↓

- Biggest benefit for starter lines with few vehicles and interconnected lines

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ESS
Barriers to widespread commercial breakthrough

SIEMENS

- ✓ Established technology
- ✓ High availability
- ✓ Promising results

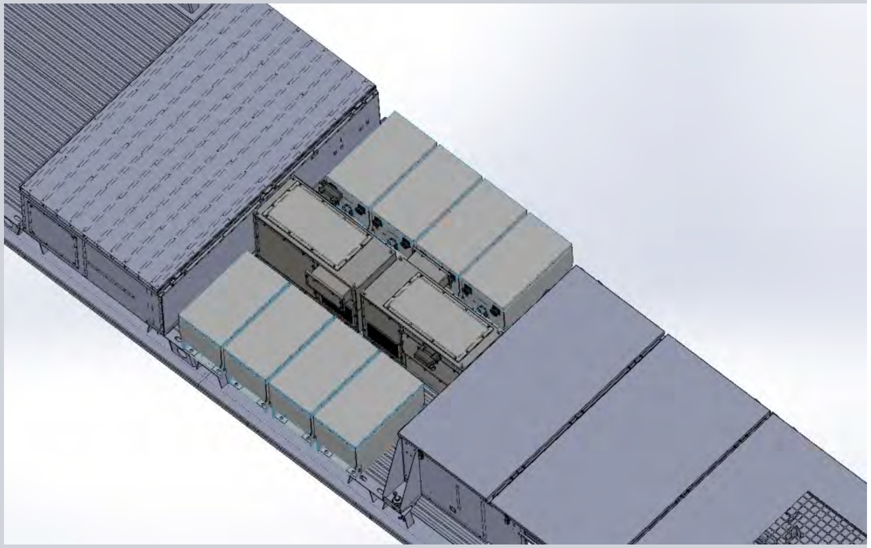
- - Uneven technological readiness
  - •(Dis-) Charging parameters of batteries and capacitors
  - •Oversized and heavy batteries with concerning chemistries
- - Return on Investment in large fleets unproven
- - Lack of true ‘off-wire’ need in key transit markets

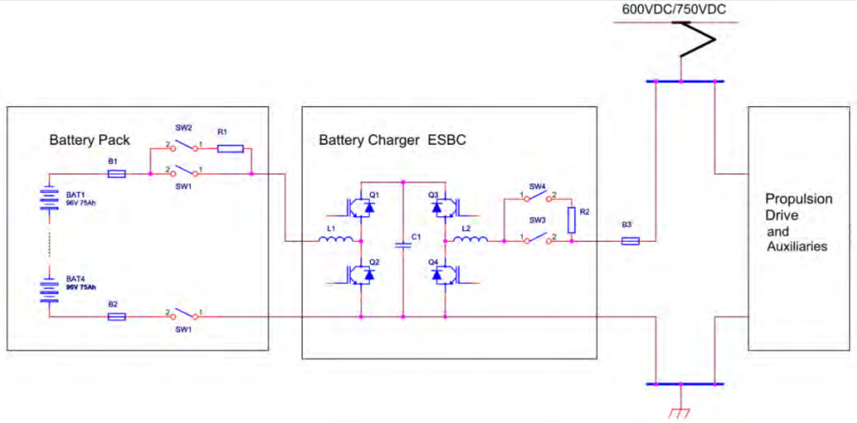
Early adopters accepting trade-offs in weight, functionality and ROI

SIEMENS

S70 Streetcar Energy Storage Concept

- Two energy saving battery (ESB) systems mounted on the roof connected to the vehicle 600/750 VDC power distribution.
- One ESB per traction container
- Batteries are away from the impacts of traffic accidents. The batteries far exceed LRV shock and vibration requirements
- Heating/cooling system will be provided to negotiate hot/cool and protecting batteries
- Estimated weight: 1170kg
- Estimated size: 52kWh
  The underlying sizing assumes a duty cycle of >2miles with multiple stops (target value)
  Real assessment of off-wire capabilities through proof of concept in summer 2013





Siemens Rail system
Creating a North American Energy Storage System

Start-up systems
urban redevelopment

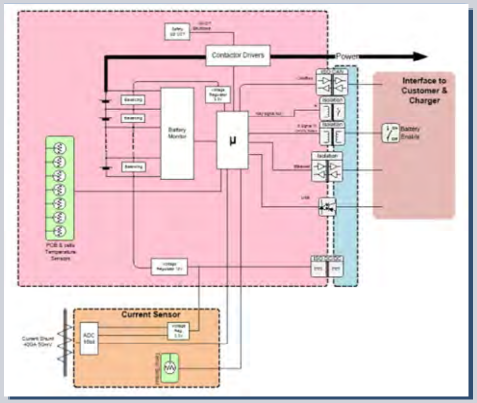
Ongoing improvement of
battery technology

Siemens
LRV market leader in North America
global portfolio
US specific requirements

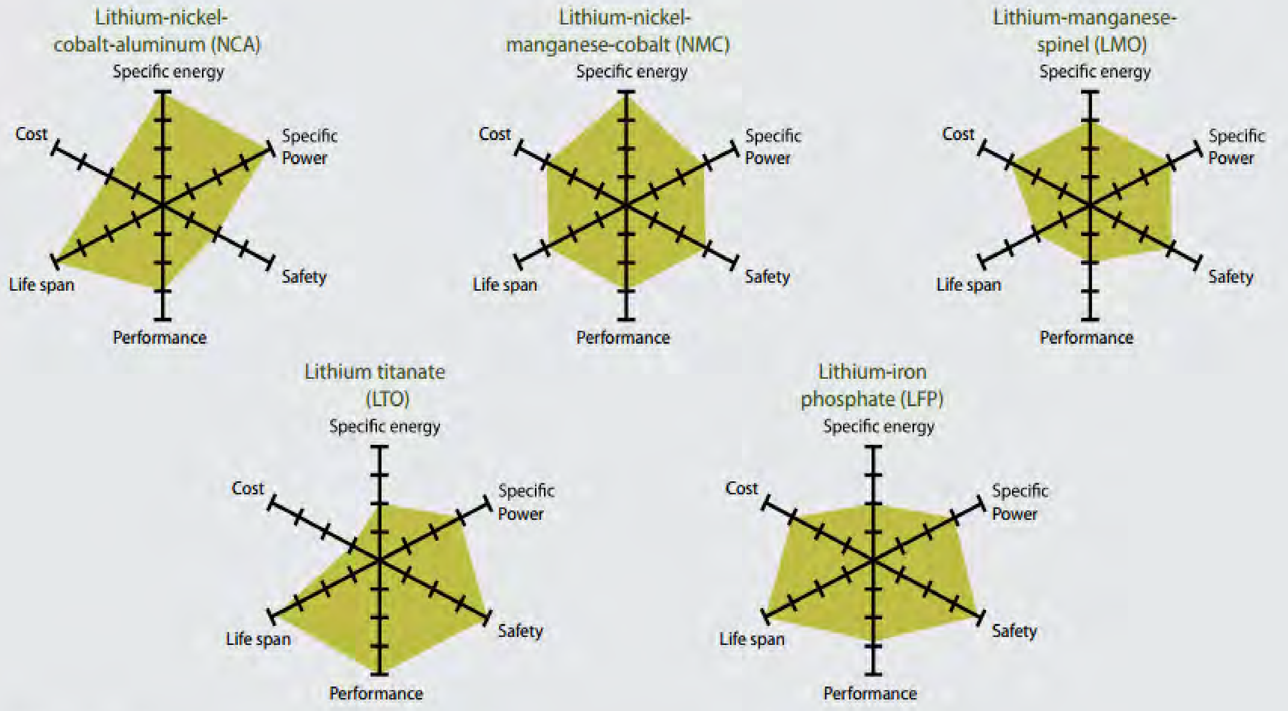
- Energy Storage System dedicated to the North American market:
  - Safe operation, low price point, ready for retrofits, targeted for US vehicles
  - Capable of energy savings and safely bridging alignment sections off-wire
- Proof of concept vehicle using the test track in the Siemens Sacramento facility : Summer '13
  - Energy saving mode
  - Off-wire operation

Backup

Batteries : cells and BMS



Battery Chemistries



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

Bombardier

WASHINGTON STREETCAR

JACQUES DROUIN
HAL LINDSEY
TIM DICKSON

BOMBARDIER
the evolution of mobility

AGENDA

1. OVERVIEW OF BOMBARDIER
2. GENERAL OVERVIEW OF THE FLEXITY FREEDOM LRV
3. FLEXITY FREEDOM OPTIONS PROCESS AND MOCK-UP
4. OVERVIEW OF BOMBARDIER SYSTEMS DIVISION
5. REVIEW OF THE SEM CONCERN
6. Q&A

This document contains financial, commercial, scientific, technical or other proprietary information. This document is for informational purposes only; is not part of any proposal; creates no contractual commitment and is subject to change

BOMBARDIER
the evolution of mobility

BOMBARDIER

OVERVIEW

Bombardier is the world's only manufacturer of both planes and trains, with a worldwide workforce of 69,800 people.

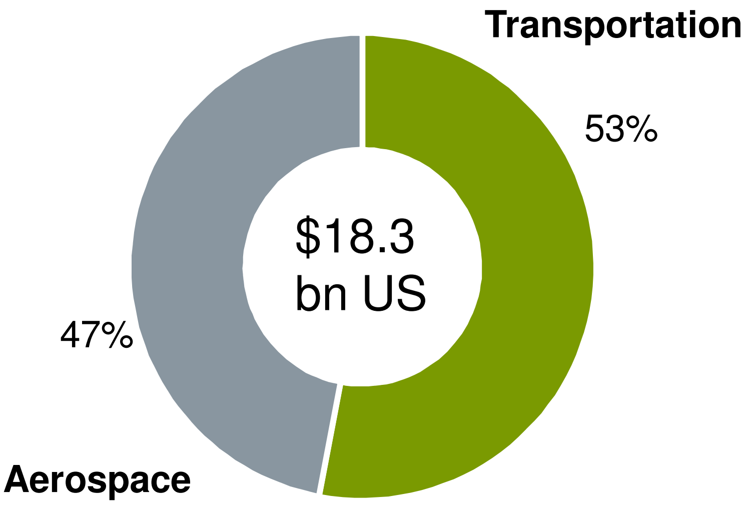
Bombardier is headquartered in Montréal, Canada. Our shares are traded on the Toronto Stock Exchange (BBD) and we are listed on the Dow Jones Sustainability World and North America indexes. In the fiscal year ended December 31, 2011, we posted revenues of $18.3 billion USD with 93% of revenues generated outside Canada.

BOMBARDIER
the evolution of mobility

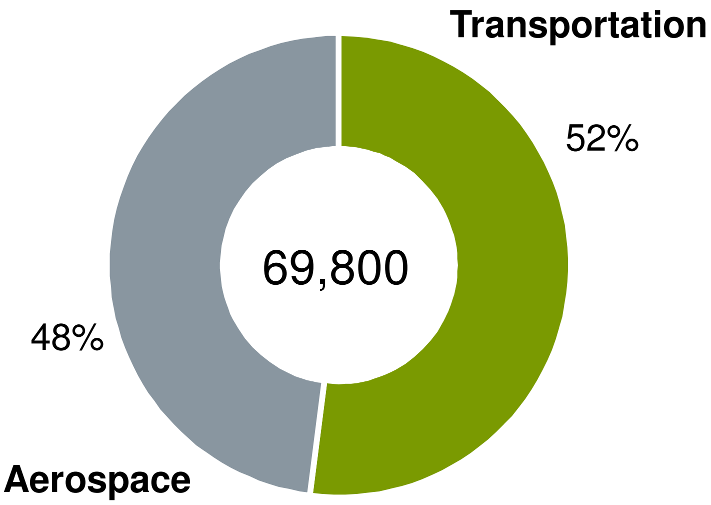
BOMBARDIER

A DIVERSIFIED COMPANY

Breakdown by revenues[1]



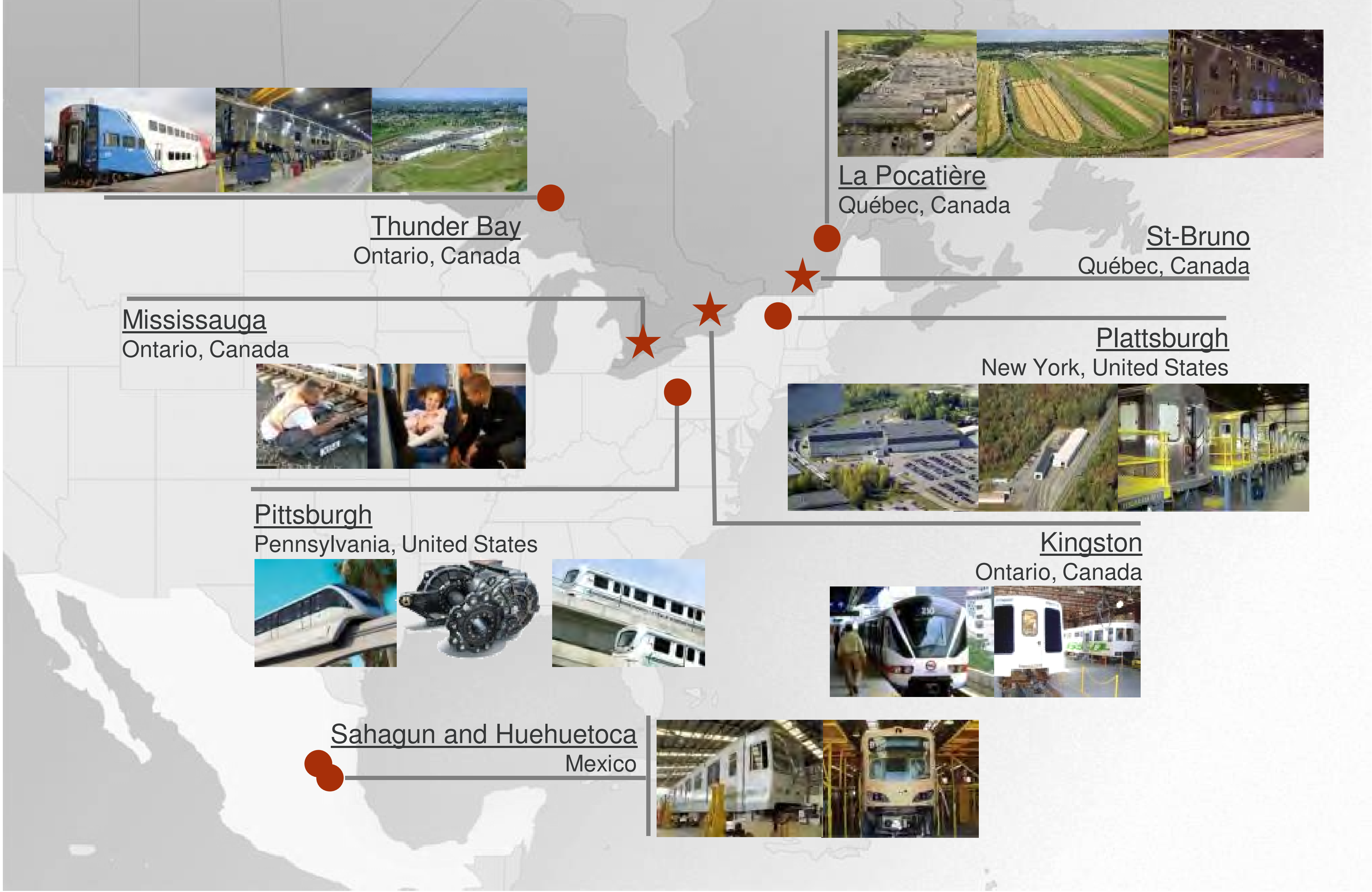
Breakdown by workforce[1]



[1] for fiscal year ended December 31, 2011

Bombardier Transportation in North America

Manufacturing Capacity and Centers of Competence



Thunder Bay
Ontario, Canada

La Pocatière
Québec, Canada

St-Bruno
Québec, Canada

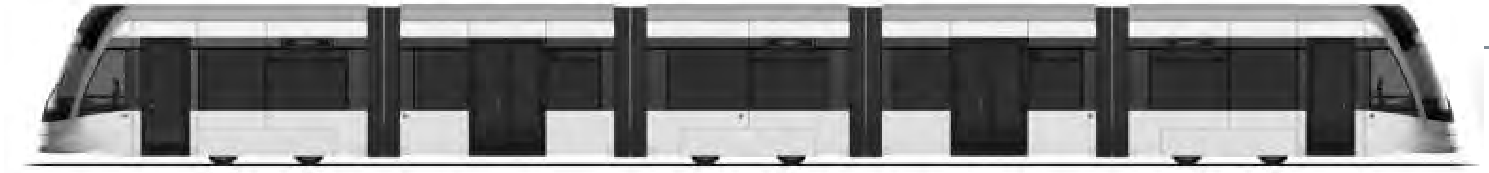
Mississauga
Ontario, Canada

Plattsburgh
New York, United States

Pittsburgh
Pennsylvania, United States

Kingston
Ontario, Canada

Sahagun and Huehuetoca
Mexico



Washington Streetcar

16 April 2013

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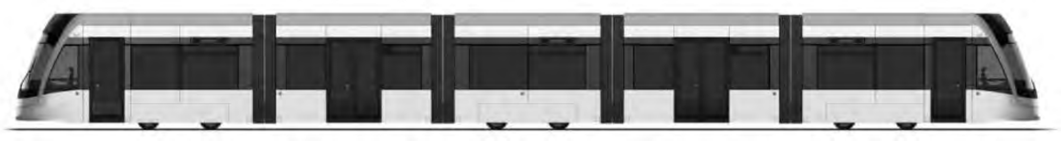
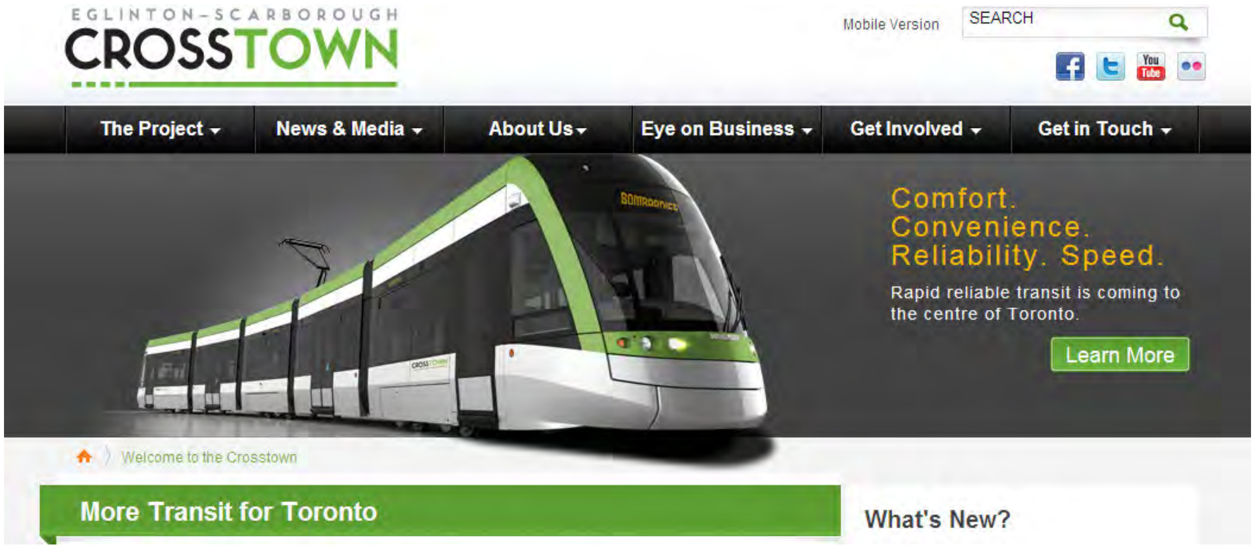
BOMBARDIER
the evolution of mobility

2 Vehicles



8 ft 8 ½ x 99 ft (2.65 m x 30.3 m)
Bi directional
Status: **in final design**

Above is the Flexity Freedom (NAFTA version of the Flexity 2)



Comfort.
Convenience.
Reliability. Speed.

Rapid reliable transit is coming to the centre of Toronto.

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BOMBARDIER *FLEXITY* 100% Low-floor trams

Main characteristics

Characteristic	Standardized platform vehicle for new and existing infrastructure
Vehicle concept	Multi-articulated vehicle
Width	2,3 m; 2,4 m and 2,65 m **(2.65 preferred for CFO)**
Bogie concept	Proven axle wheel set bogie with primary suspension and low unsprung mass
Gauges	1000 and 1435 mm
Motor technology	Water cooled asynchronous motors
Buffer load	400 kN
Carbody concept	Welded steel carbody
Bogie area – floor layout	6% longitudinal ramps over bogie, small platforms above bogie, 5% transversal ramps

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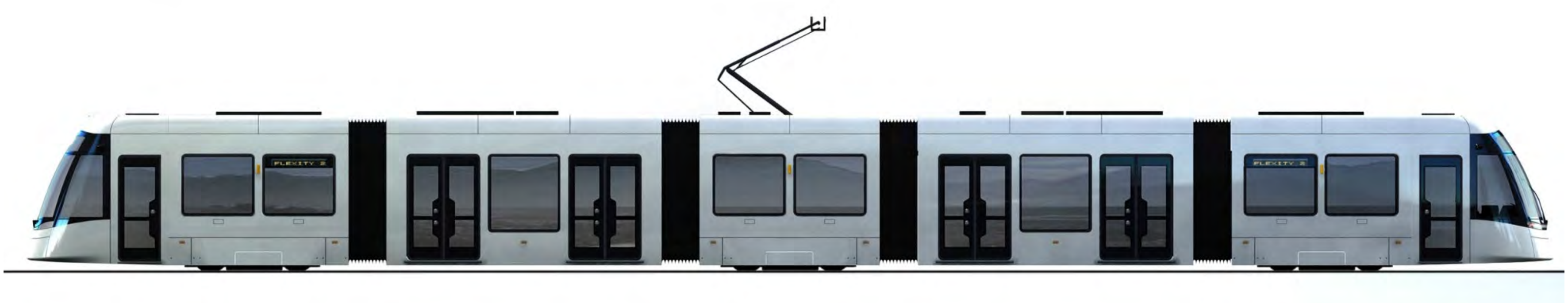

European Flexity 2, very similar design

2 Vehicle Features

- ✓ Modular design
- ✓ 100% low floor
- ✓ Conventional axle bogies
- ✓ Accessibility
- ✓ Vehicle dimensions
- ✓ Peformance
- ✓ Operation
- ✓ Winter Operation
- ✓ Safety and CEM

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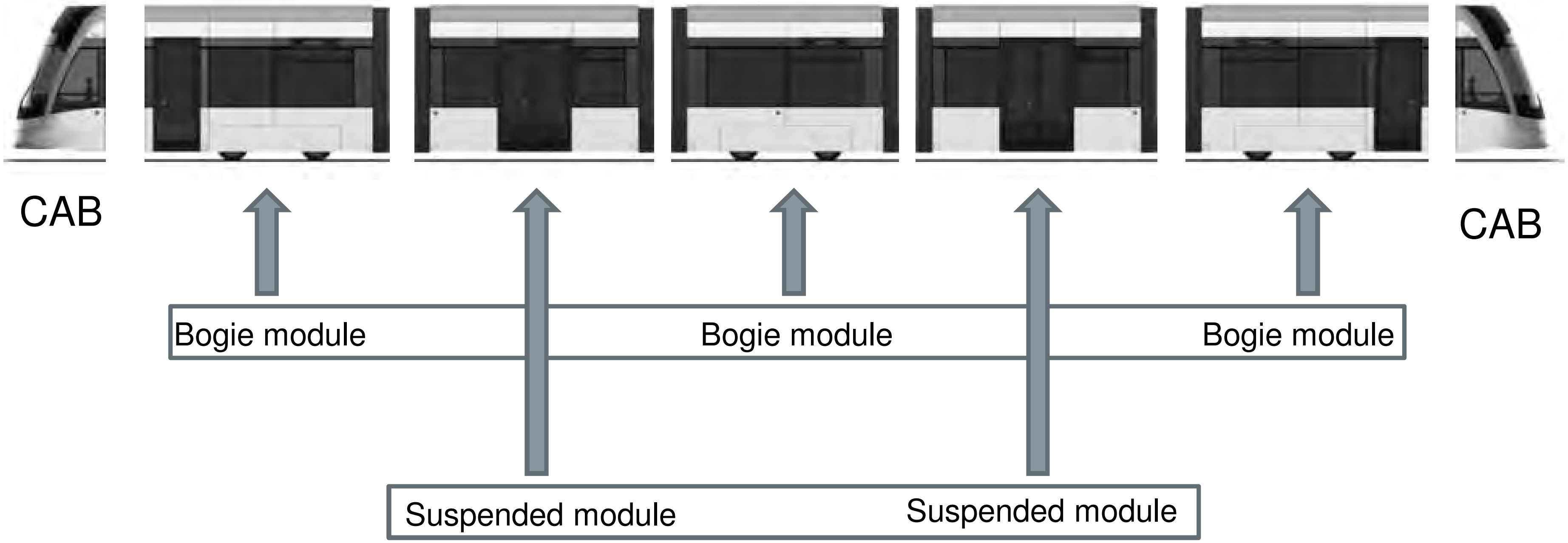
2 Vehicle Features – Modular design



CAB

Bogie module

Suspended module

Bogie module

Suspended module

Bogie module

CAB

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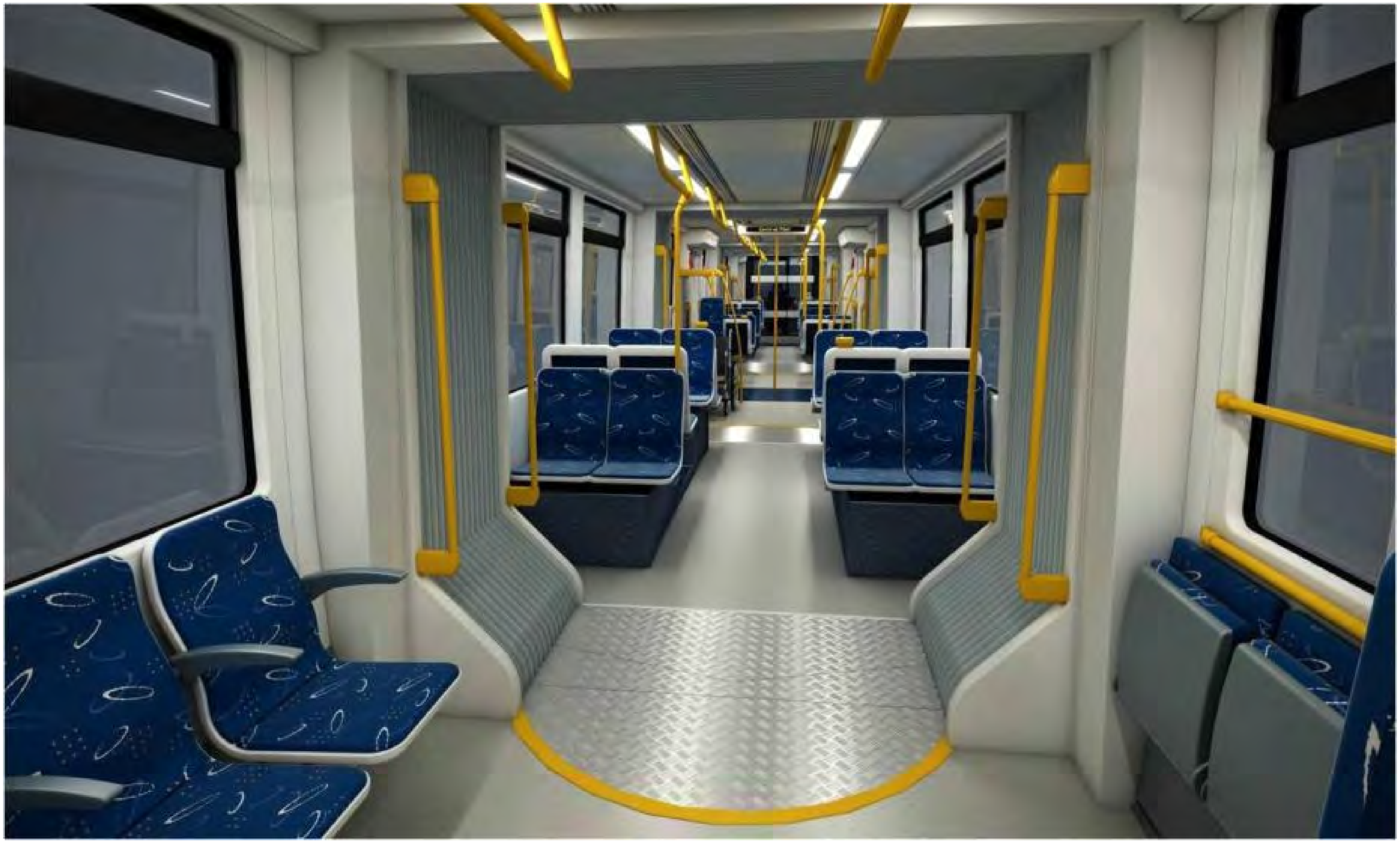
2 Vehicle Features – 100 % low floor



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2 Vehicle Features – 100 % low floor

Easy boarding
through wide double doors

Minimal dwell time, more
efficient line

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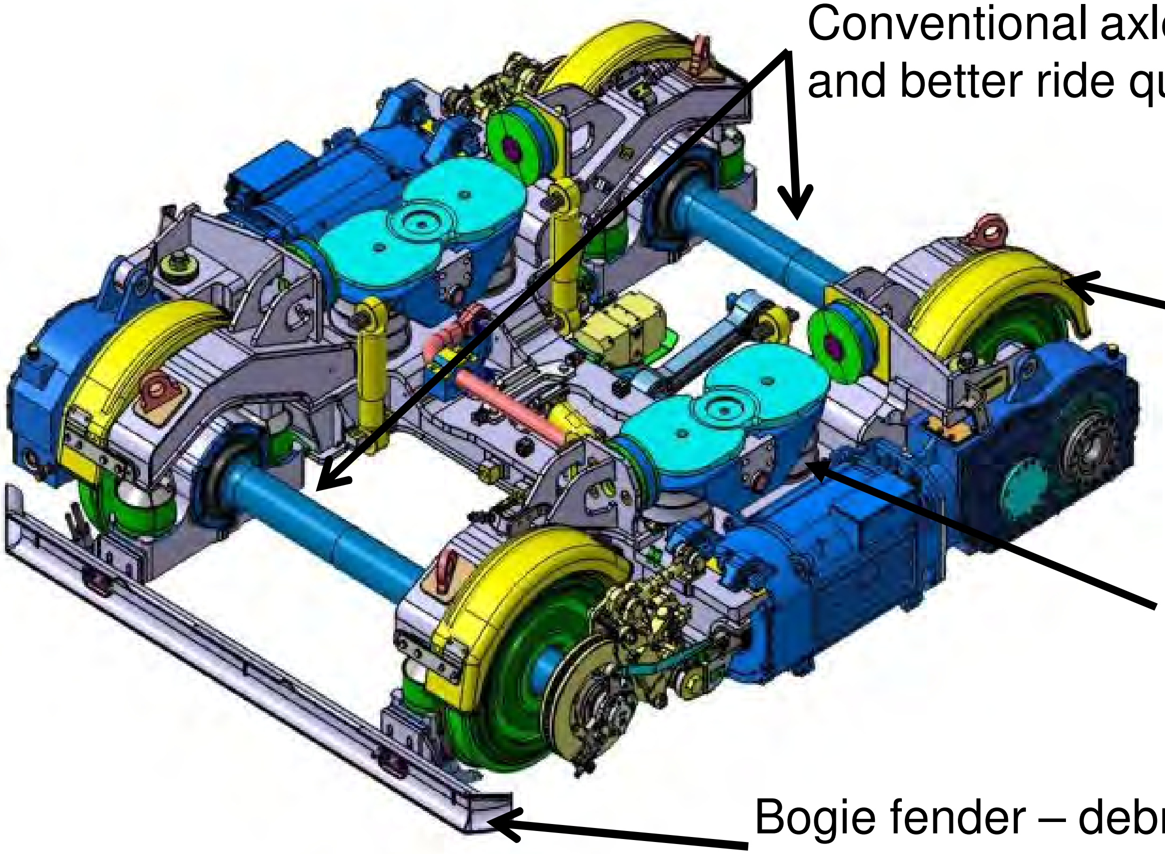
2 Vehicle Features – Conventional axle bogies



Conventional axle bogies for minimal wear and better ride quality

Wheel guard

Hydraulic load leveling

Bogie fender – debris/snow clearing (leading axle)

Motorized bogie

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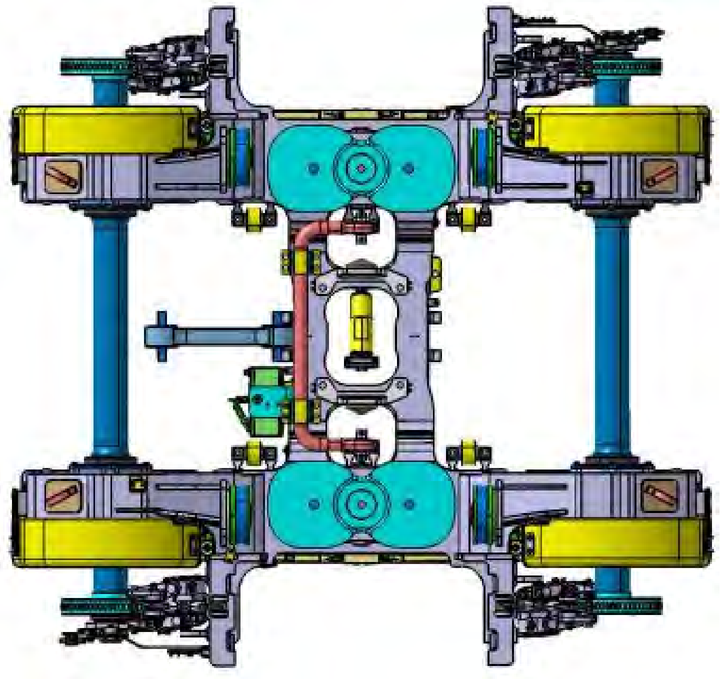
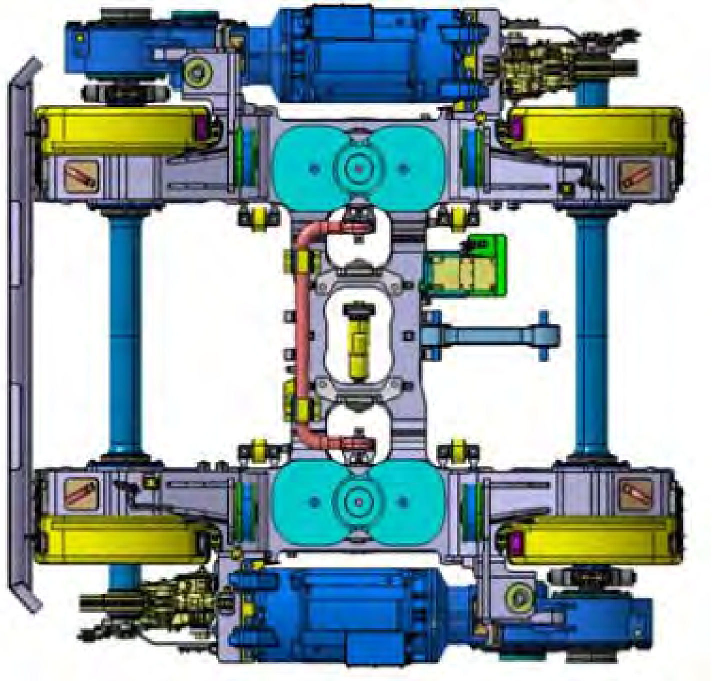
2 Vehicle Features – Conventional axle bogies



Four discs per truck
(2 per axle)

Trailer bogie



2 motors/2 gearboxes
2 discs per truck

Motor bogie

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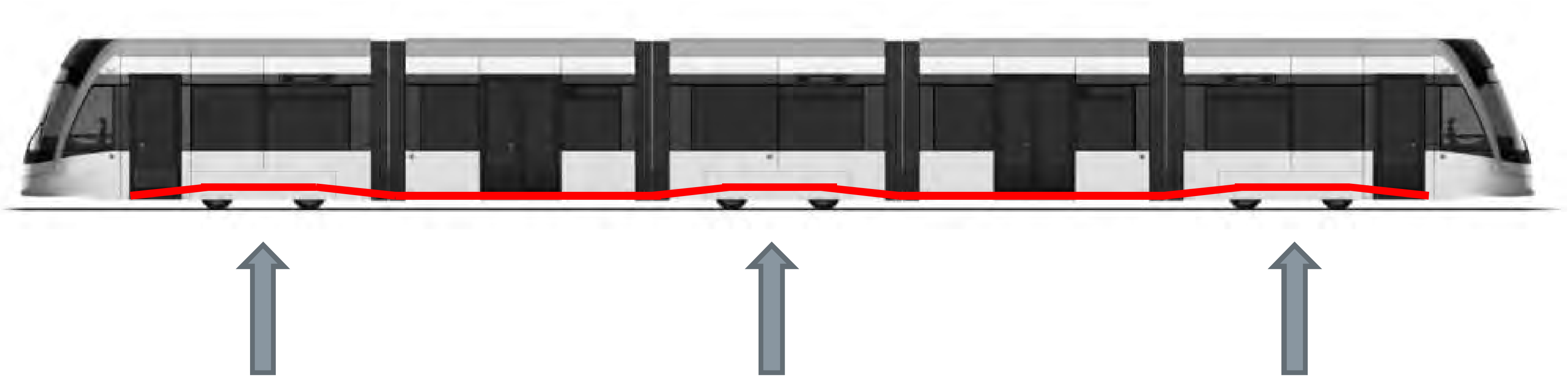
2 Vehicle Features – Conventional axle bogies



Motorized bogie

Trailer bogie

Motorized bogie

The floor is slightly raised to clear the bogie axles

The slopes remain within the prescribed limits of mobility impaired passenger requirements (ADA)

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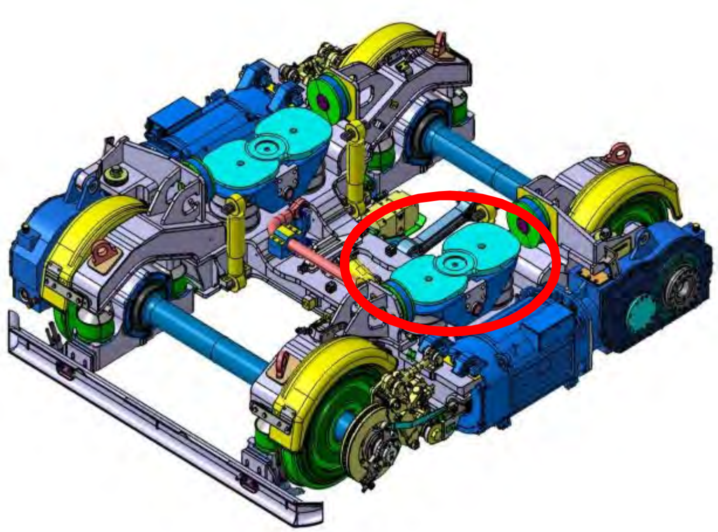
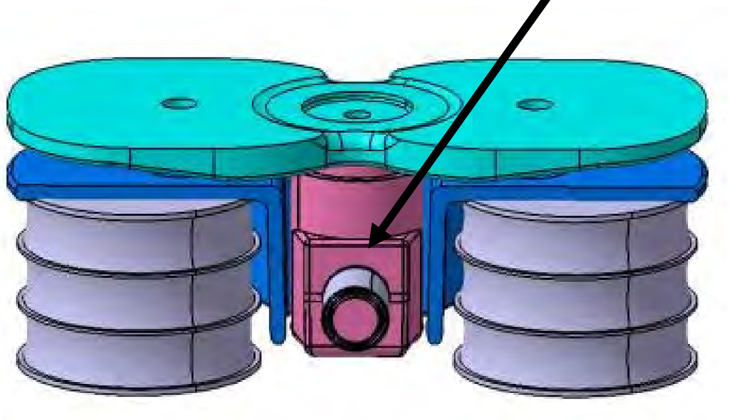
2 Vehicle Features – Accessibility – Car leveling





Hydraulic load leveling

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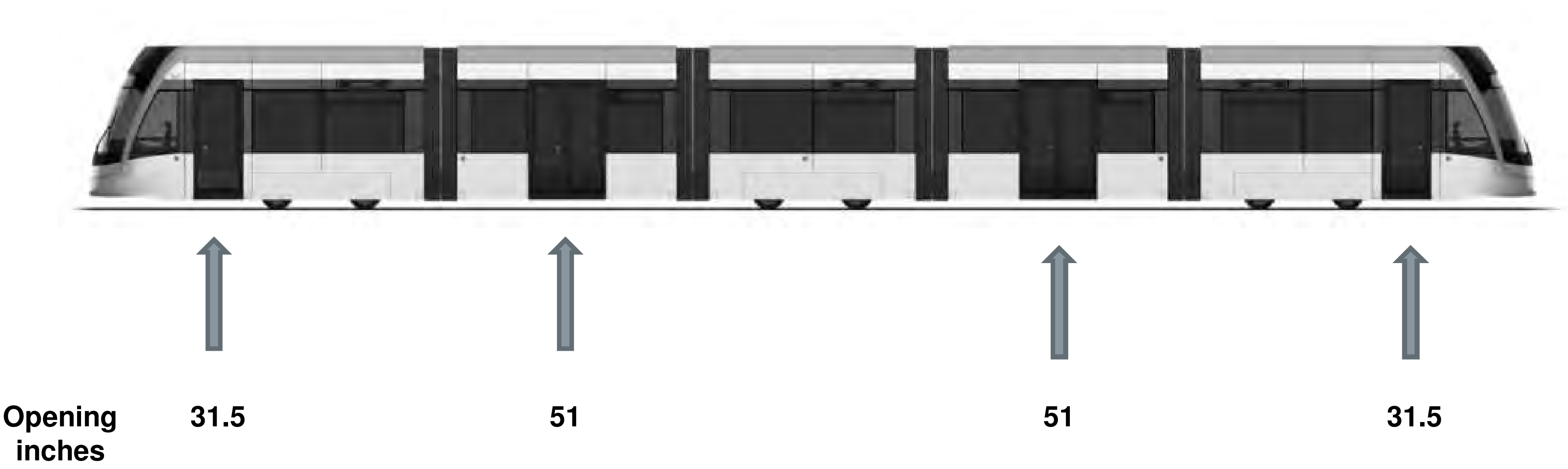
2 Vehicle Features – Accessibility – Passenger doors



2 wider doors for the mobility impaired area
2 doors at the end to mimimize dwell time and ensure passenger flow
Configuration is suited for minimum dwell time while maximizing comfort

Doors are electrically operated slide and plug motion with obstruction detection:
-Better noise reduction inside
-Better climate control
-Aesthetically pleasing: flush with carbody

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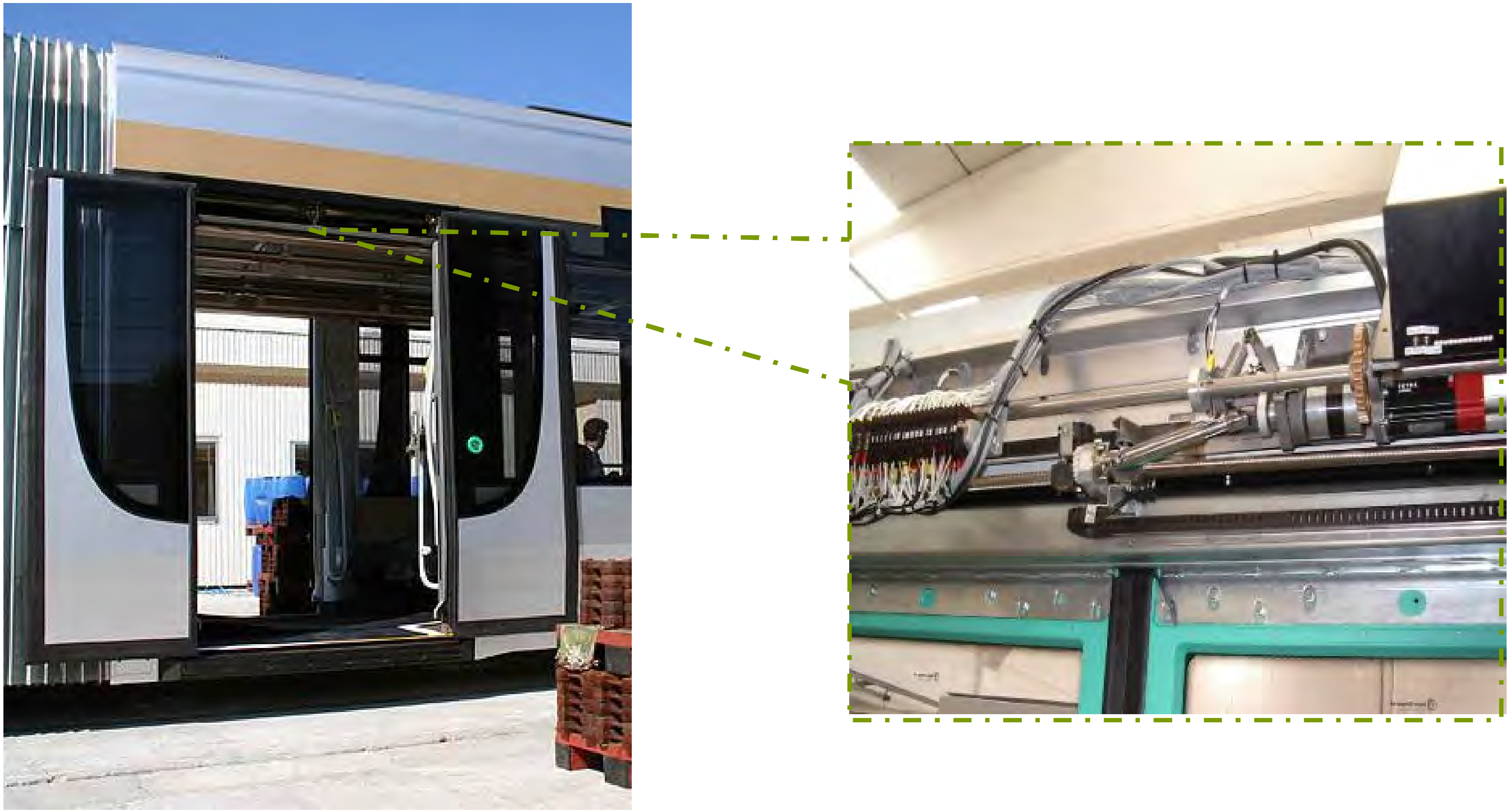
2 Vehicle Features – Accessibility – Passenger doors

Bi-parting plug sliding door (double door) and door actuator



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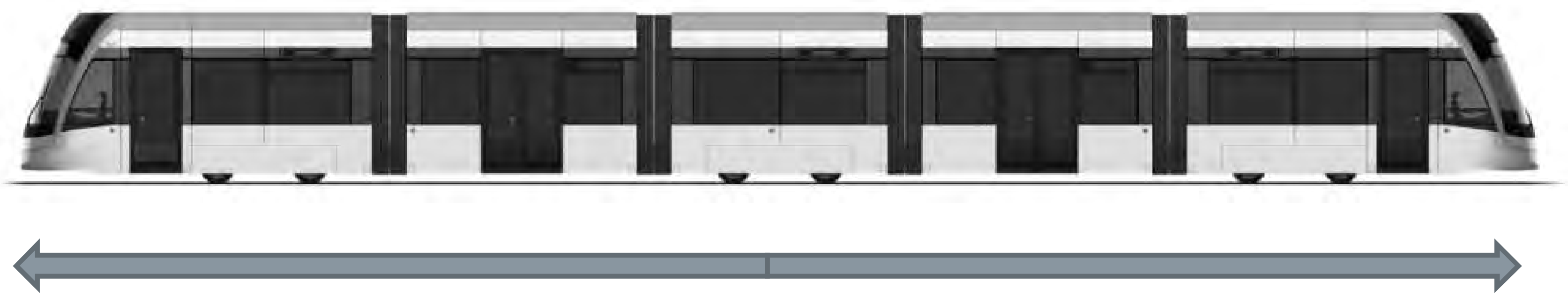
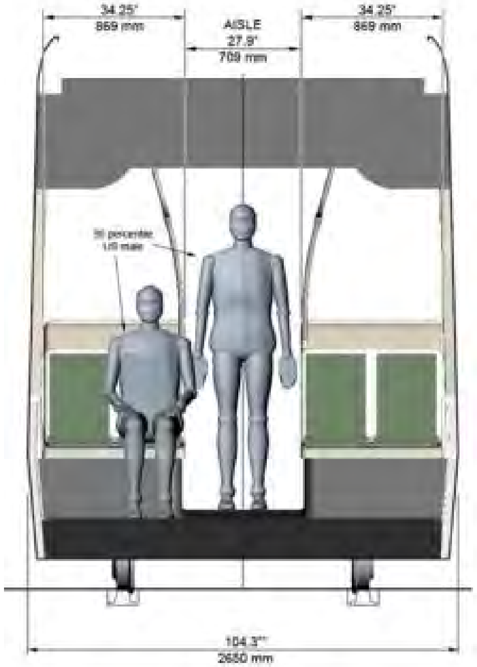
2 Vehicle Features – Dimensions



Length: 98 ft



Width is 8ft 8 in ½ (2.65 m), allowing for comfortable 2 x 2 seating

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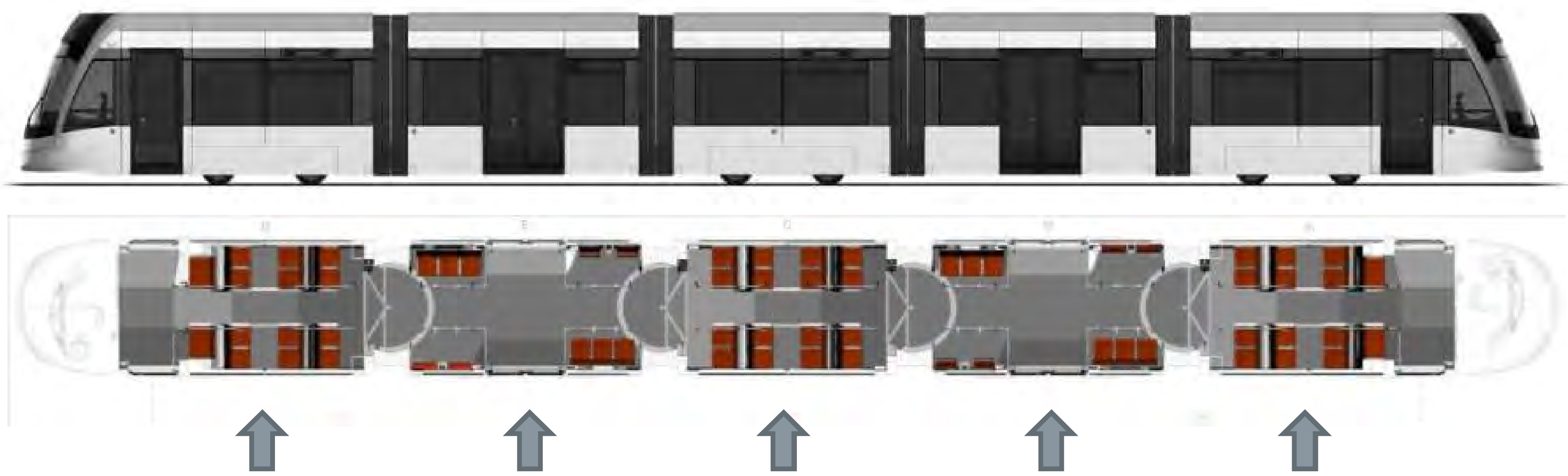
2 Vehicle Features – Dimensions



Fixed | **Flexible** | **Fixed** | **Flexible** | **Fixed**

Seating arrangement

Seated	56
Flip up seats	8
Wheelchair areas	4
Standees	130 (4 pass/m²)

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2 Vehicle Features – Peformance

Maximum service speed	80 km/hr	50 mph
Maximum acceleration	1.2 m/s²	2.7 mphps
Service deceleration	1.2 m/s²	2.7 mphps
Emergency brake rate	2.77 m/s²	6.2 mphps
Grade capability	6 % (250 m)	6% (820 ft)

Using Bombardier's service proven Mitrac propulsion package

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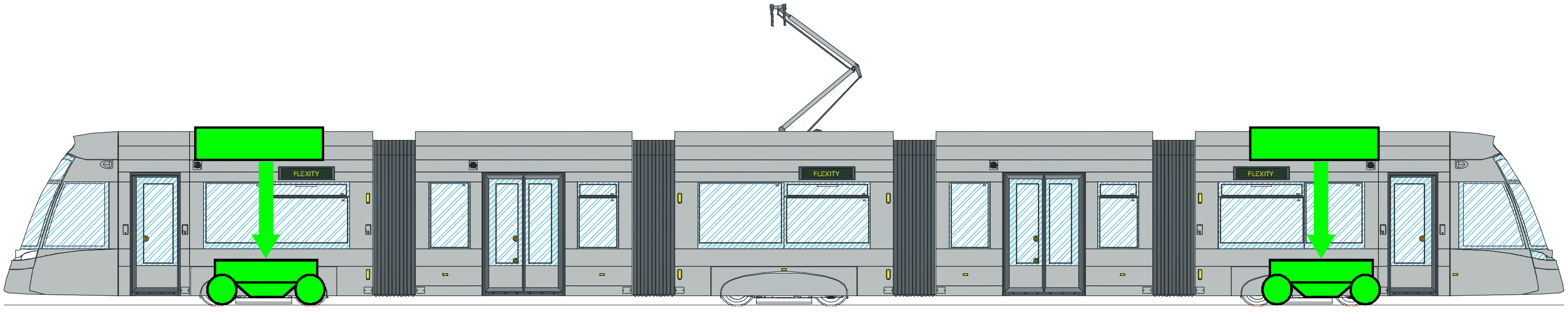
2 Vehicle Features – Performance - Propulsion



Mono Converter *MITRAC* TC 530 (13SG65)

- With one power module (one CM-H module)
- Capable to drive one bogie (2 motors)

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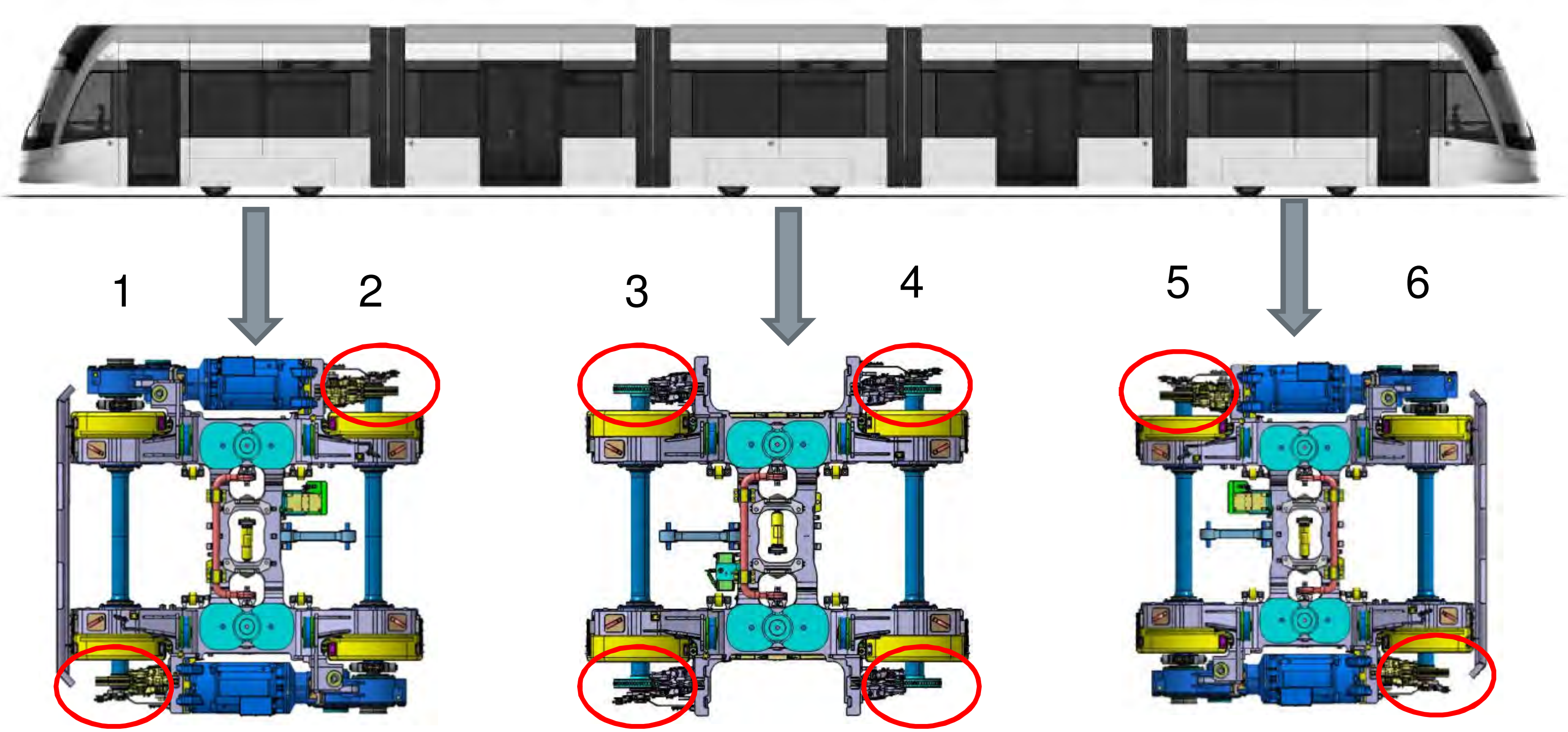
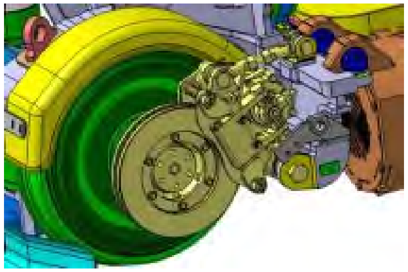
2 Vehicle Features – Performance - Brakes



Hydraulic disc brakes – no susceptibility to humidity infiltration (winter)
Lighter and more compact



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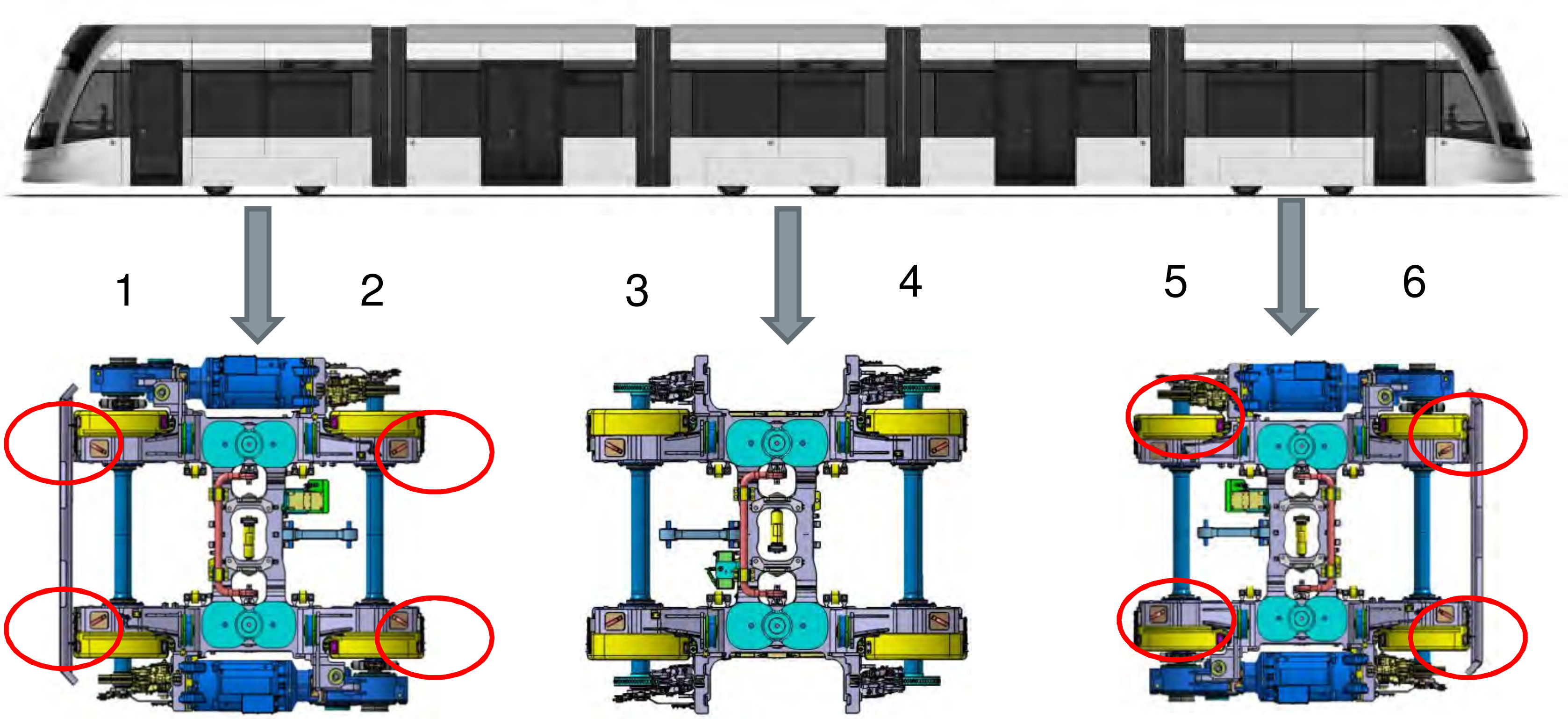
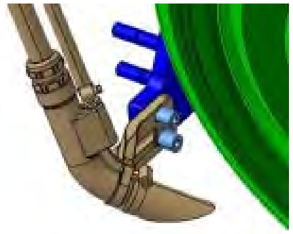
2 Vehicle Features – Performance - Brakes





Sanding nozzles are provided on axles 1, 2, 5 and 6
The sander itself is installed in the car and is pressurized

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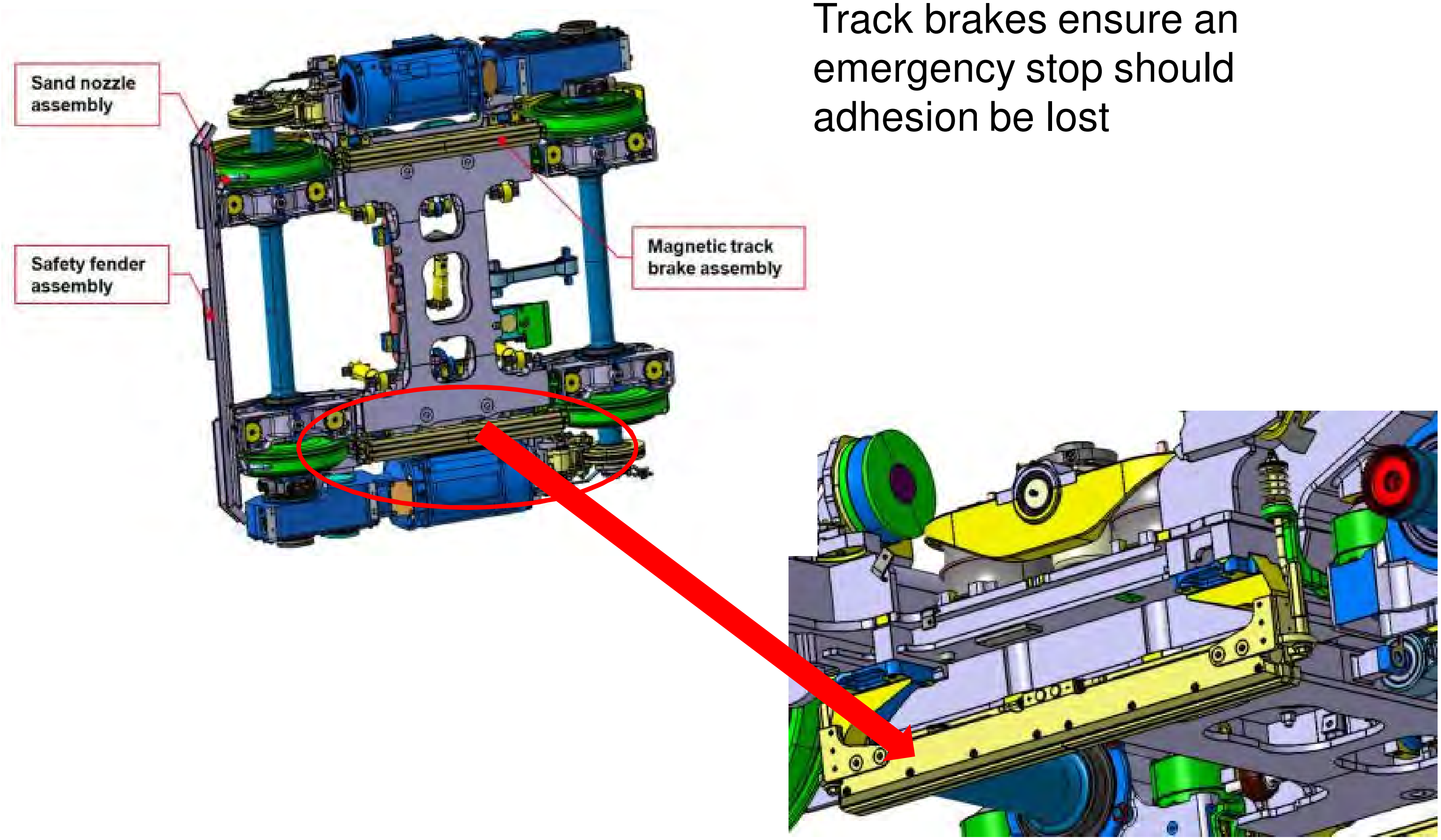
2 Vehicle Features – Performance – Track Brakes



Track brakes ensure an emergency stop should adhesion be lost

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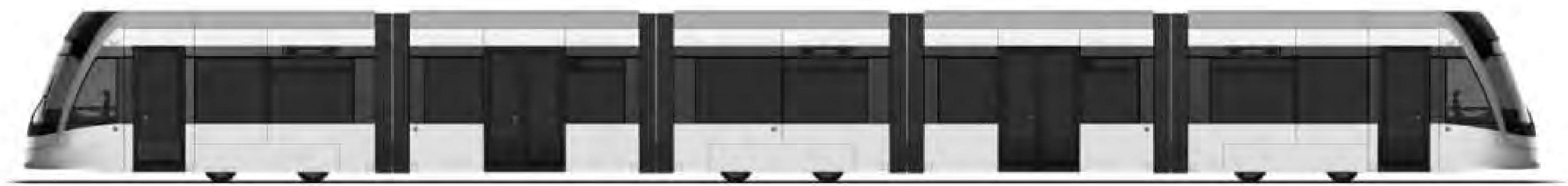
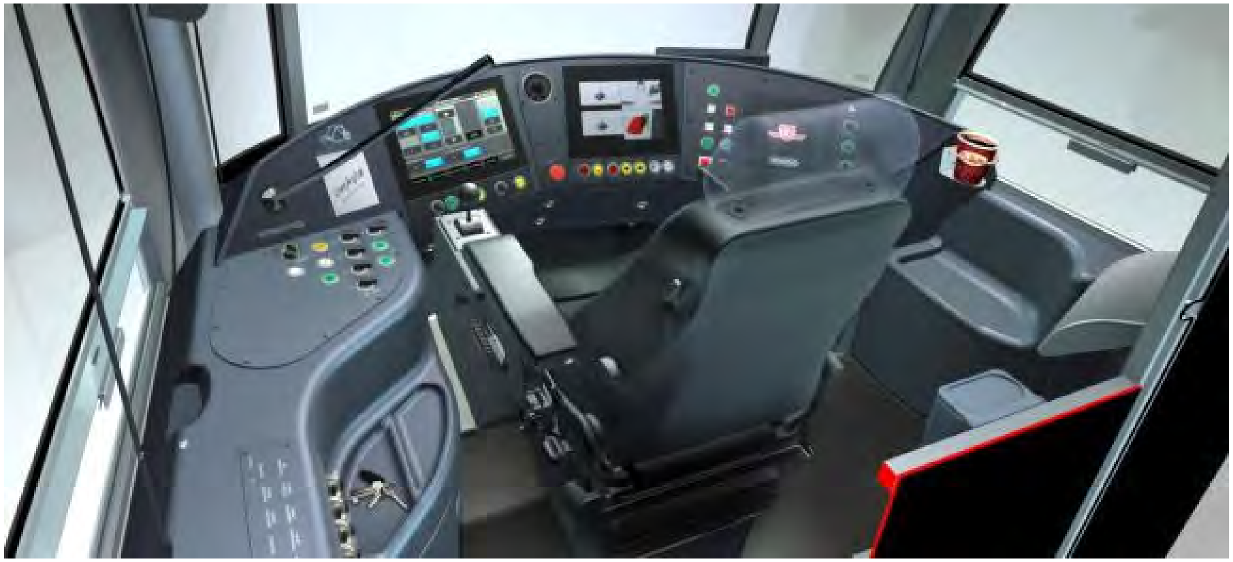
2 Vehicle Features – Operation

Full cab width at both ends, the vehicle is bi-directional





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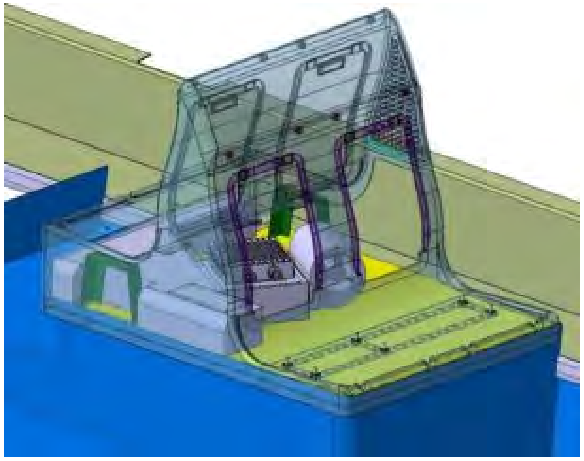
2 Vehicle Features – Operation - Winter

- Load cases for the vehicle structure allow for snow accumulation on the roof (14'' or 355mm).
- Heated surfaces: door thresholds, coupler heads (mechanical and electrical), windshield, sanding ejectors.
- 28 KW of forced air floor heater (passenger area).
- Independent sanders are provided.
- Snow/debris fender on the leading axle of motor trucks.
- Bogies equipped with mud/snow guards.
- Stainless steel side and underframe structures



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2 Visibility

The cab ergonomic study ensured maximum visibility for the driver while still allowing for the necessary structural strength to be built in.

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Content

BOMBARDIER solution for CFO (Catenary Free Operation)

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Flexity Freedom

Thank you

Washington

BOMBARDIER

Primove
for
Washington Streetcar

2013.04.18

BOMBARDIER
the evolution of mobility

Agenda

- ☐ INTRODUCTION TO PRIMOVE
- ☐ ANSWERS TO QUESTIONS
- ☐
- ☐
- ☐

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Easy Urban Mobility

Contactless and catenary-free electric operation

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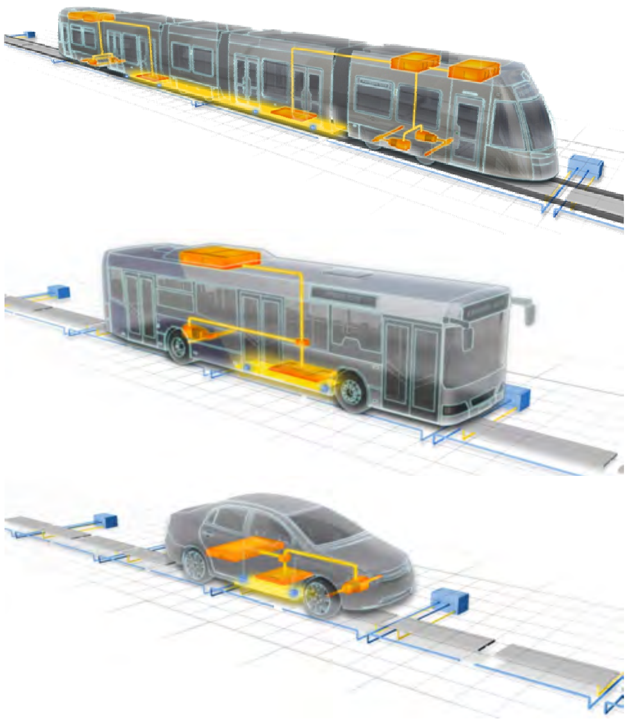
primove e-mobility

Game changing solution for all types of electric vehicles



One infrastructure for all electric vehicles

Wireless inductive power transfer

Unlimited mobility and no recharging hassles

Underground – safe, invisible and tamper-proof

Zero emissions and low maintenance

Project partners:

FLANDERS DRIVE · NXP · Vrije Universiteit Brussel · ENERGYICT · KATHOLIEKE UNIVERSITEIT LEUVEN · VANHOOL · inverto · OCW · VOLVO · infrax · Mobistar

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primove e-mobility

Ready now!

Augsburg, Germany

Phase 1 – Tram:	2010 - 2012
Phase 2 – Minivan:	since Q1 2012

Lommel, Belgium

Phase 1 – Bus:	since Jan 2011
Phase 2 – Car:	since Q1 2012

Mannheim, Germany

Phase 1 – Test lab:	since Sep 2011
Phase 2 – Minivan:	since Sep 2011
Phase 3 – Bus:	since 2011

Application to trams, buses, cars and commercial vehicles

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primove *Rail*

The most advanced caternary-free technology available

Invisible, no visual pollution.

Components hidden under the vehicle and beneath the track

Safe inductive power transfer (IPT)

Non-contact, no wearing of parts

All-weather performance

Customizable to specific needs of every city, including:

- diverse performance expectations
- varying distances
- Different topographical conditions
- Brownfield or greenfield

Easy to Install

Same performance as with catenary system

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Advantages of primove *Rail:* Safe

The *PRIMOVE* system is compliant to all applicable codes and standards for electromagnetic compatibility

No health or safety hazard to passengers and pedestrians as all electric devices are fully isolated

No interference with other systems and equipment

No impact on electrical appliances like mobile phones or heart pacemakers

- Bombardier works closely with independent assessors to establish top standards for safety

Pacemaker Testing

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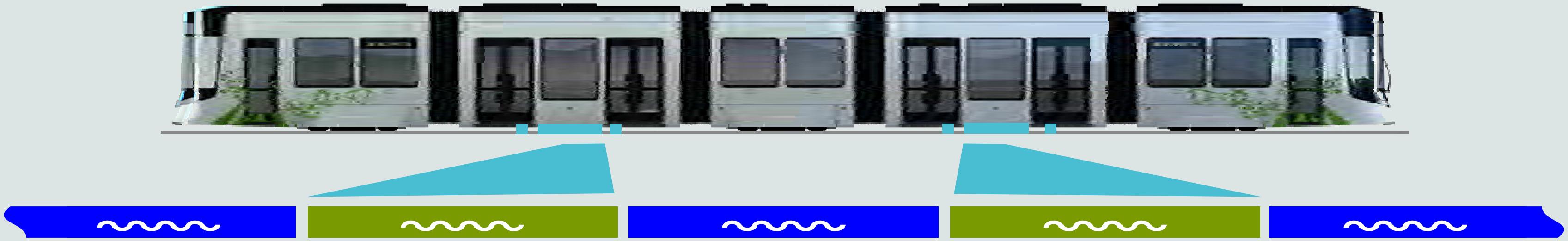
Advantages of primove *Rail:*
Safe

Electromagnetic fields are only created under the vehicle



NOT like primove

Antennas, such as for mobile phones, spread magnetic fields all around
Comparable with a sprinkler where everything in the vicinity gets wet

Like primove

primove technology directs the magnetic fields to the vehicle – the magnetic field is contained

Comparable to a tap where water comes out in a flow without watering everything around

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Advantages of primove *Rail:*
Safe

- Safe to touch
- No exposed wiring like third rail or catenary
- Multiple redundant safety systems
- Even in catastrophic failure the magnetic field exposure does not lead to injury.

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Advantages of primove *Rail:*
Reliable

- Vehicle operation even under adverse weather and ground conditions
- No risk of power loss due to contact break – unlike other ground power supply technology

- Redundancy of overhead lines and poles clears the view for impressive cityscapes, landmark buildings or green areas

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Advantages of primove *Rail:*
Reliable

Runs in sand, snow, salty slush

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primove *Rail*
Options: Full CFO or CFO+Catenary

Complete CFO system

We recommend:

- primove at stations, on grades, or at crossings, where needed
- Straight-forward and cost effective approach, especially for new systems

Catenary and CFO combination

We recommend:

- Energy storage solution for CFO needed between a few stops only
- primove plus energy storage where CFO is desired on longer distances

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primove *Rail*
Applications: Greenfield or Brownfield

Greenfield or long CFO

We recommend:

- primove at stations, on grades, or at crossings, where needed

Brownfield or short CFO sections

We recommend:

- Energy storage plus catenary for short CFO sections
- primove system plus energy storage for wireless operation

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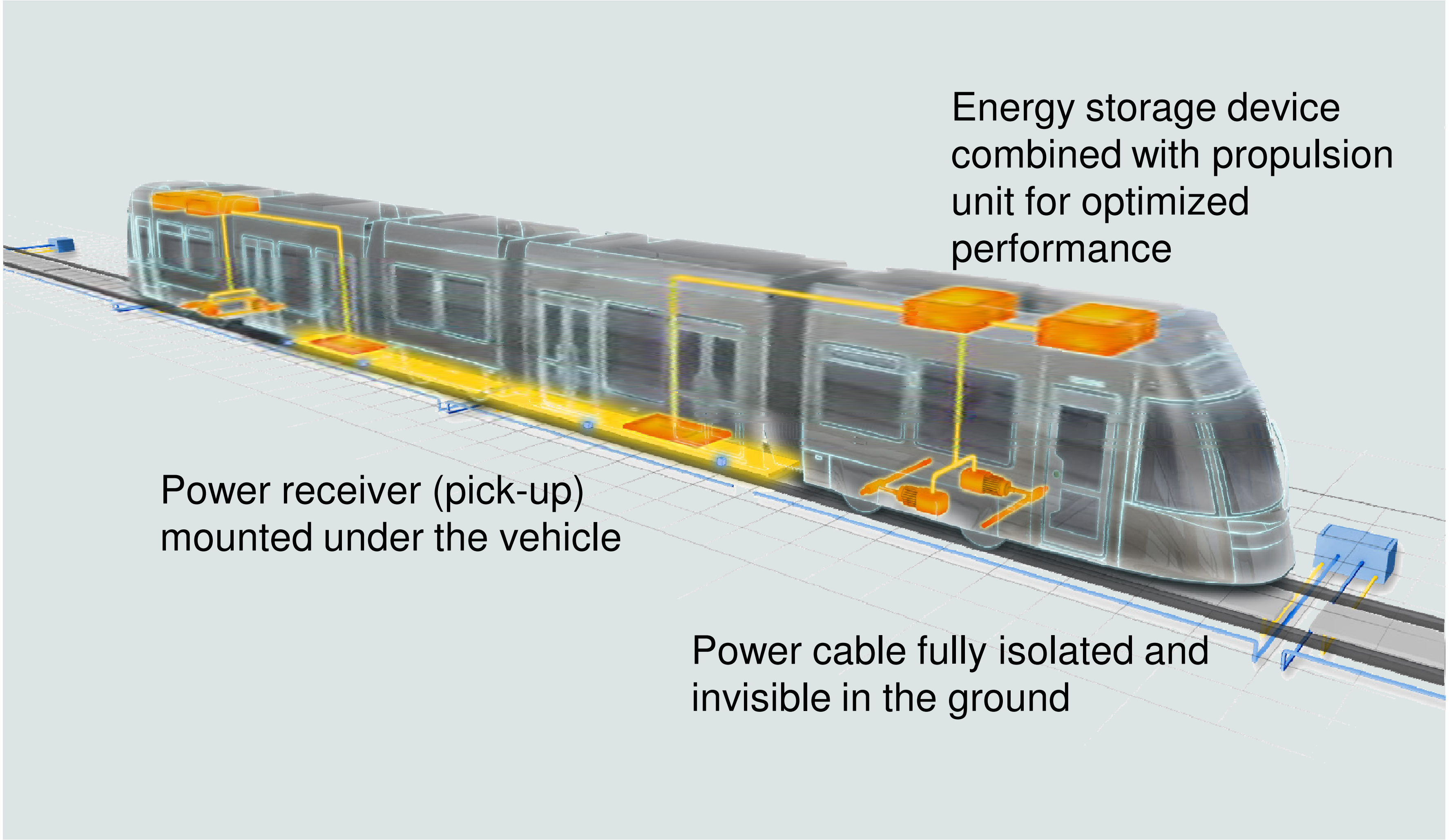
BOMBARDIER
the evolution of mobility

primove *Rail*
Inductive Power Transfer Technology



Energy storage device combined with propulsion unit for optimized performance

Power receiver (pick-up) mounted under the vehicle

Power cable fully isolated and invisible in the ground

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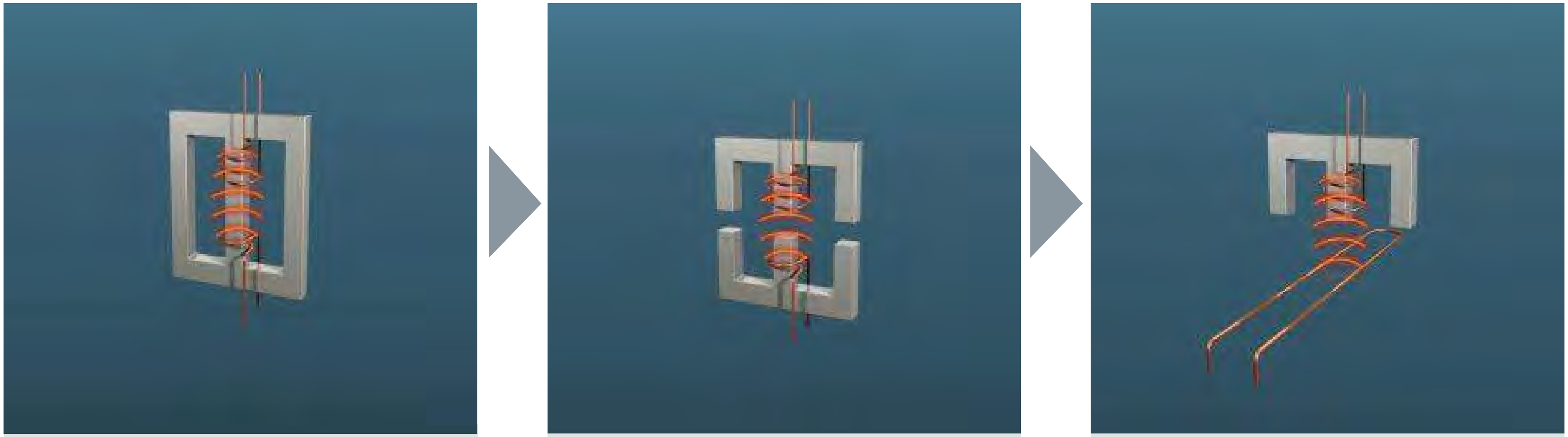
primove *Rail*
Fundamental Principle

The inductive principle has been well known for many years. It can now set new standards in electric mobility:



Schematic principle of a transformer

- Iron core
- Primary and secondary windings

Iron core can be split

- Air gap between primary and secondary winding possible

Primary side can be modified

- Primary winding around iron core can be replaced by several cables

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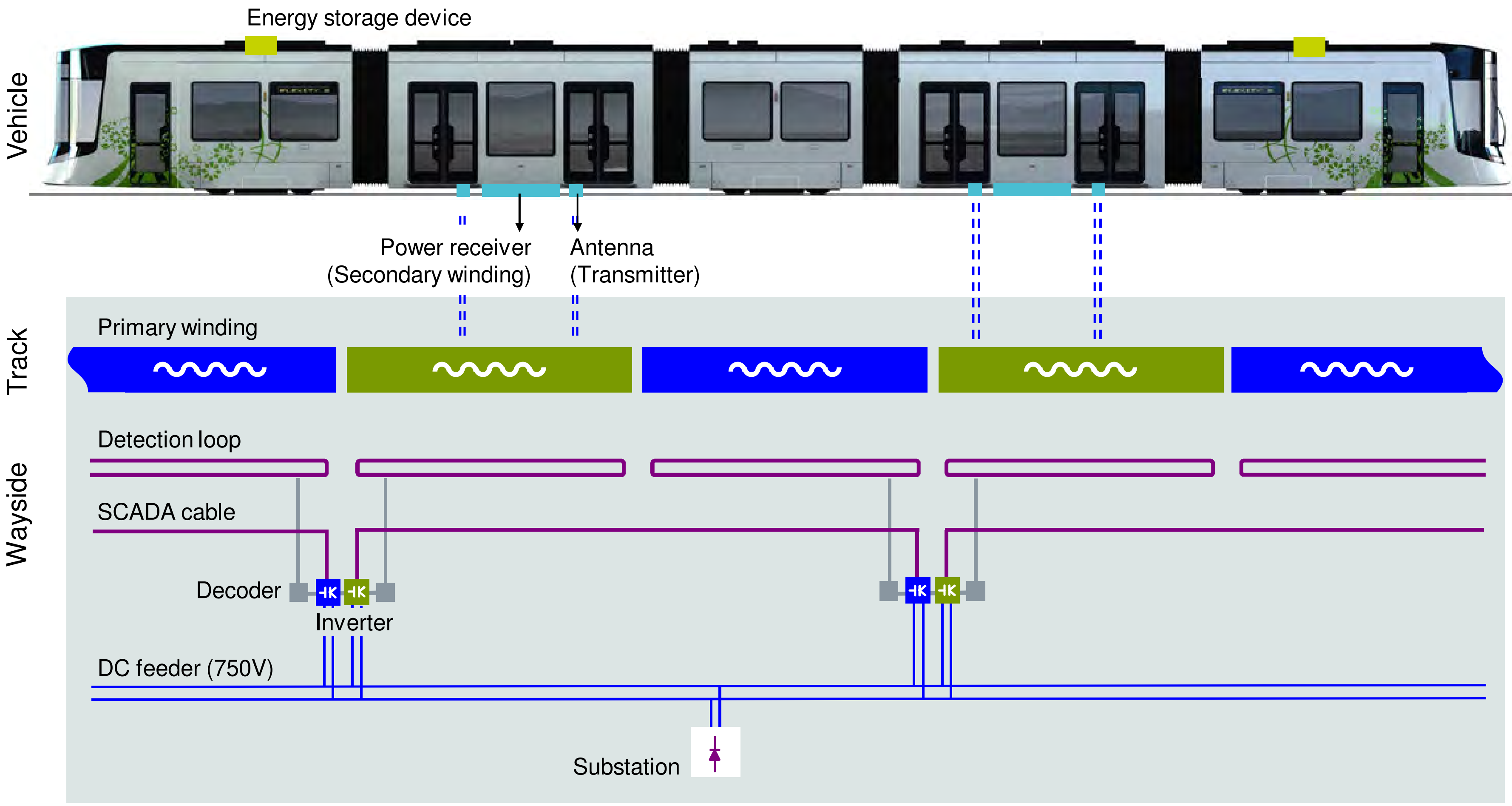
primove *Rail*
System Components



Vehicle

Track

Wayside

Energy storage device

Power receiver
(Secondary winding)

Antenna
(Transmitter)

Primary winding

Detection loop

SCADA cable

Decoder

Inverter

DC feeder (750V)

Substation

🟨 Energy storage device 🟦 *PRIMOVE* CFO solution

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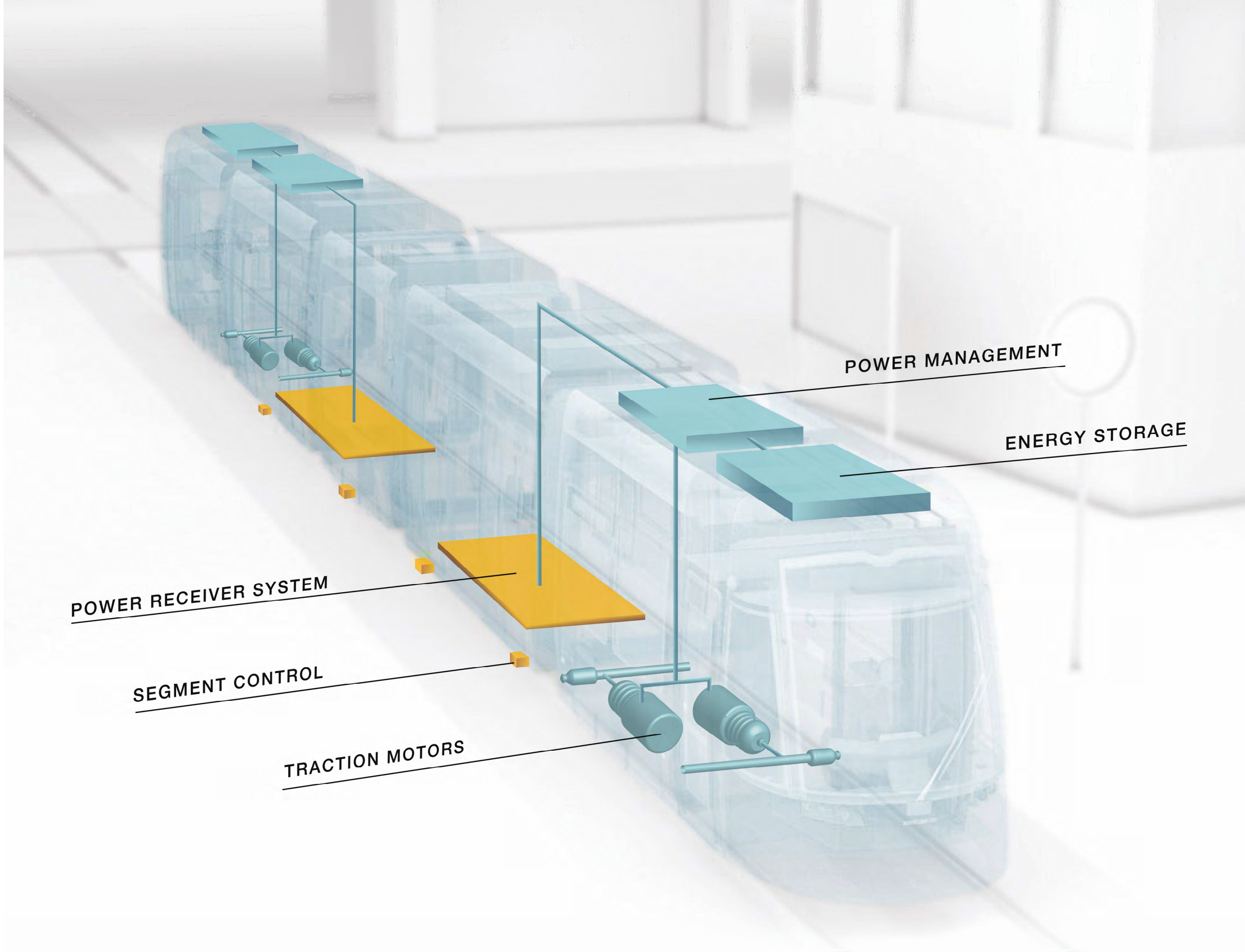
primove *Rail*
Vehicle Components



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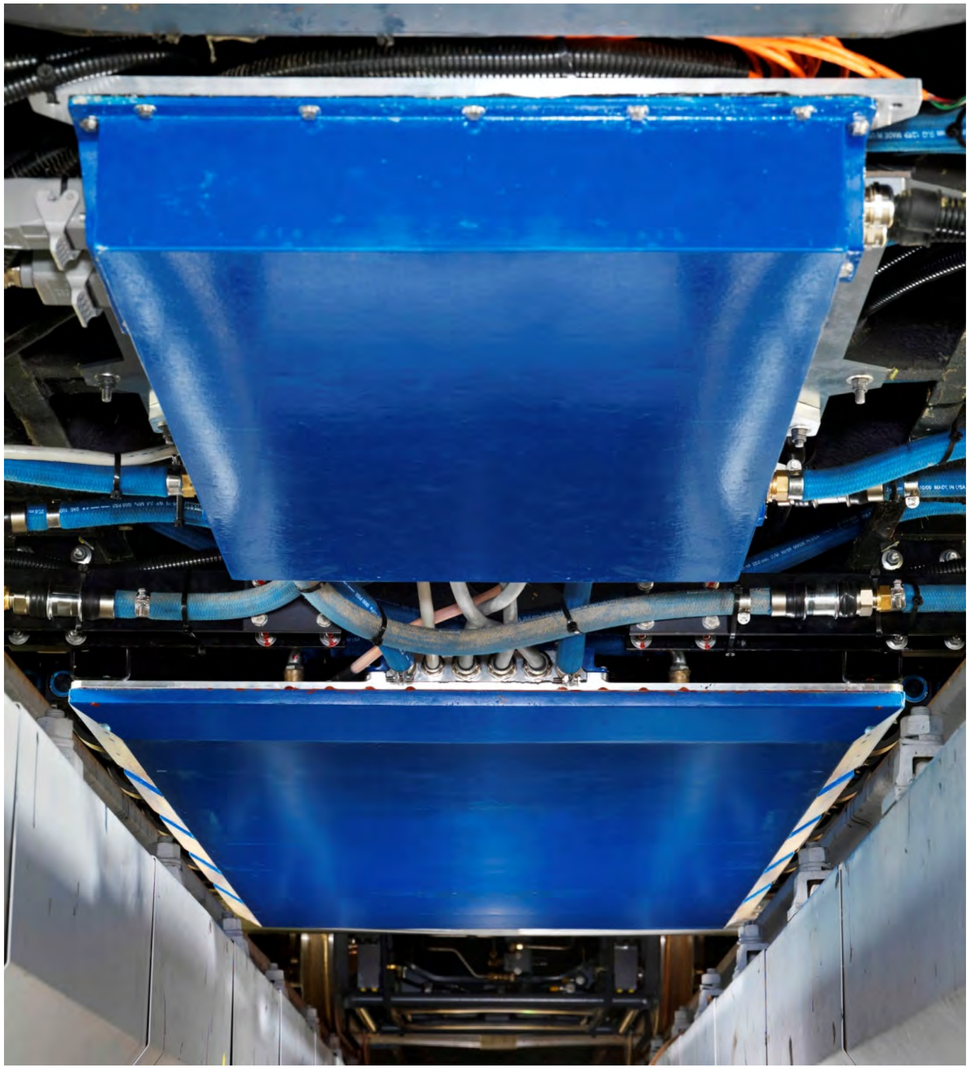
primove *Rail*
Vehicle Power Receiver (Generation 2)



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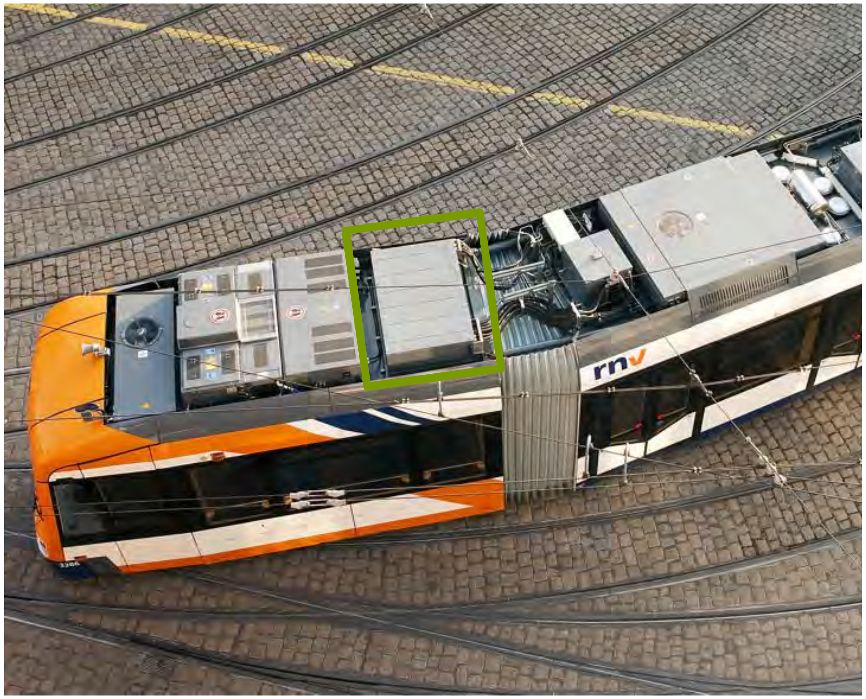
primove *Rail*
Energy Saver on Vehicle

Energy storage device stores electrical energy released when braking

- **Energy savings up to 30% for light rail systems**
- **Boost to the vehicle’s power for higher acceleration**
- **Optimization of power supply**
- **Reduced infrastructure investment**
- **Catenary-free operation for short distances and as a part of the primove solution for longer distances**



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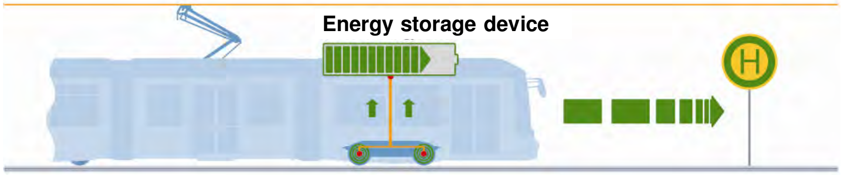
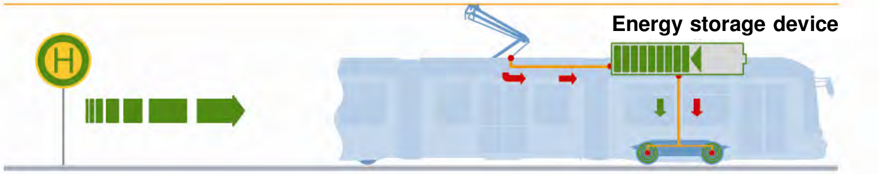
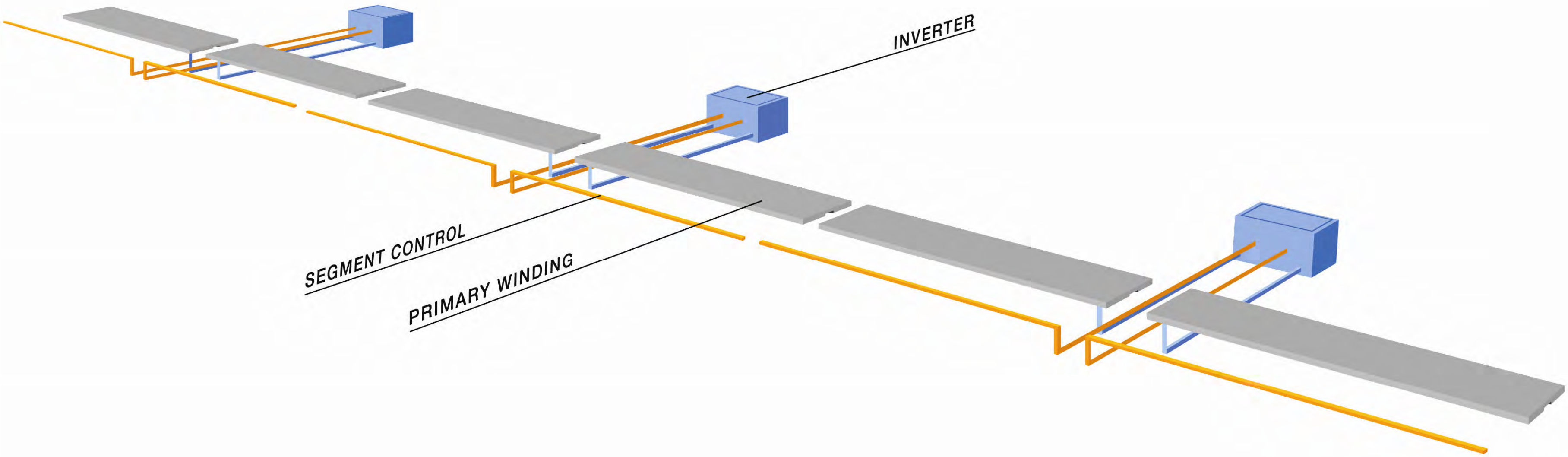


Storing energy while braking



Using stored energy during acceleration

primove *Rail*
Wayside and Track Elements, Schematic



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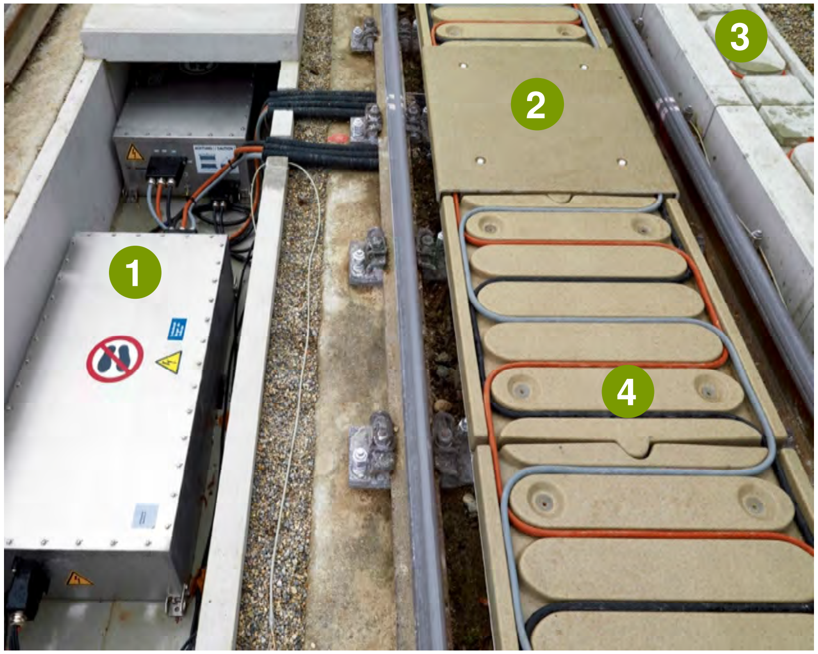
primove *Rail*
Wayside and Track Elements, Actual



1 Inverter
2 Cover
3 Detection loop
4 Cable support

- Windings are easy to install
- All components are pre-tested and certified prior to commissioning
- Existing tracks can be easily modified to allow installation of wayside components
- Track and wayside components are completely covered to allow movement of normal traffic over the track area

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the evolution of mobility

primove *Rail*
Wayside and Track Elements, Installation

All *PRIMOVE* wayside components fit completely in the envelope of the vehicle

No additional foundation required

- Maximum depth below top of rail: less than 600mm

Primary windings fit completely between rails

Less land surface needed than for catenary systems

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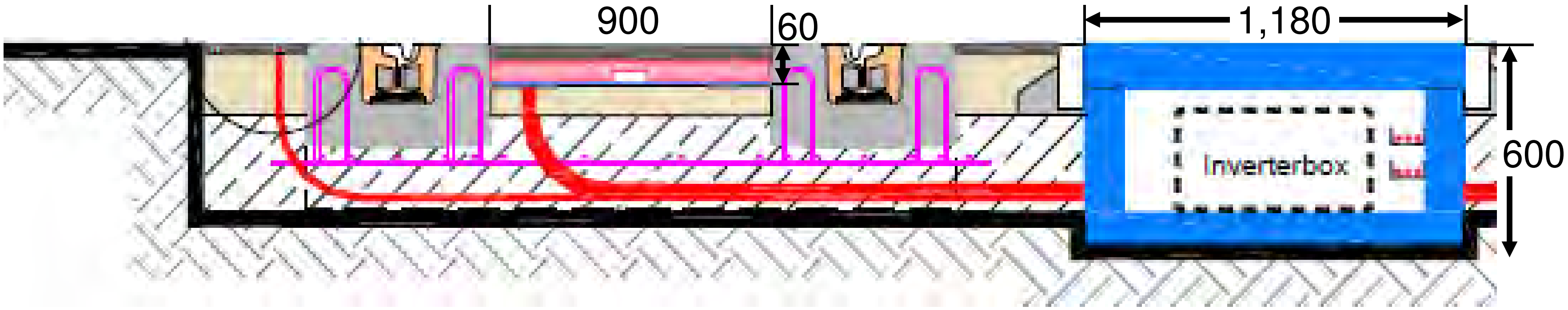

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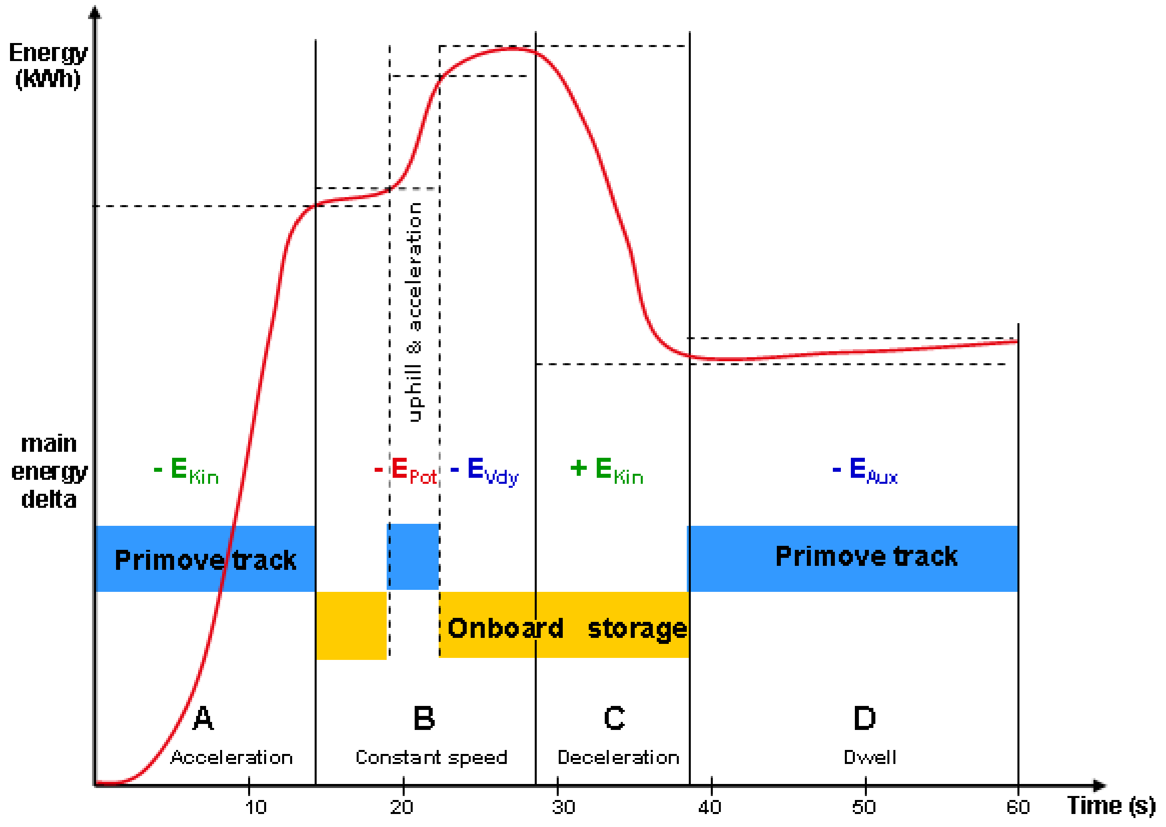
primove *Rail*
primove Energy Management



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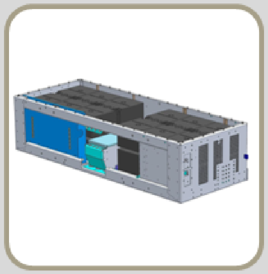
primove *Rail*
Batteries and Supercaps

MITRAC Energy saver (Supercaps)

- Energy saving (ES) operation with good efficiency.
- Cost-effective solution for ES.
- CFO for short distances.
- Series product since 2009
- Over 3 million km driven to date.



Traction battery

- Battery is a good solution for CFO applications due to the large amount of stored energy – long range.
- Battery is cost effective for CFO.

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primove Rail

Answers to questions are
on the following pages

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primove *Rail*
Questions & Answers

Question #1: CFO Reference projects

Rail: Augsburg Germany (more on next page), projects pending

Bus: Lommel Belgium, Brugge Belgium, Braunsweig Germany, Mannheim Germany

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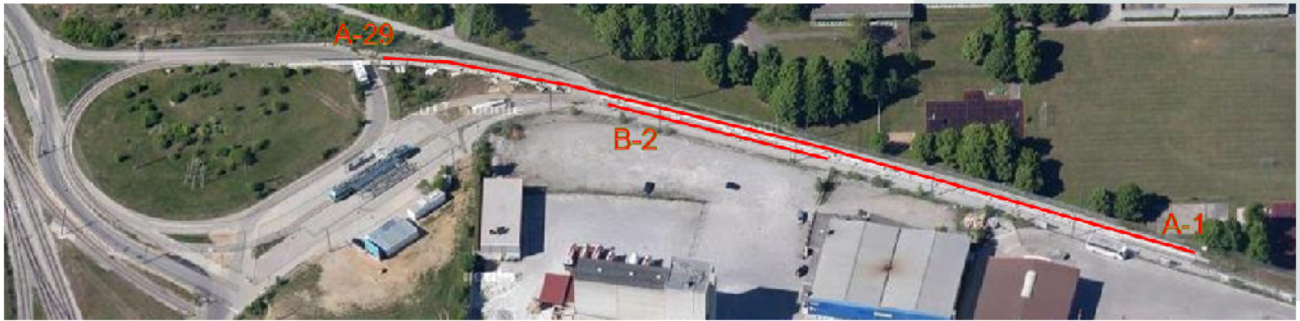
primove *Rail*
Augsburg Pilot

Demonstrated the system's technical capability and compliance with all standards for electromagnetic compatibility under real conditions of operation in urban environment



Bundesministerium
für Verkehr, Bau
und Stadtentwicklung

Co-funded by the German Federal Ministry for Transport, Building and Urban Development (BMVBS)

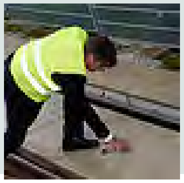
Stadtwerke
Augsburg

Realised in cooperation with the Augsburg Transport Authority (Stadtwerke Augsburg Verkehrs GmbH)

Continuous power transfer, dynamic & static

2x100 kW power max

Safe



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◄ Status

primove *Rail*
Questions & Answers

Question #2: PS&D*, mixed catenary & CFO operation

Primove can be installed in three configurations: 100% primove wireless and catenary-free power transfer, primove charging at stops and critical locations, or mixed caternary and CFO, no primove charging segments.

Primove – 100% CFO

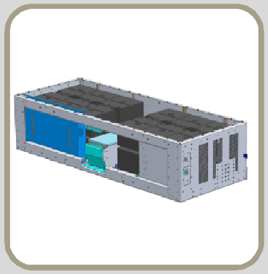
- Invisible
- Reliable under all weather conditions
- Charging can be located where needed , for exp. Crossing, slope ...
- Safe

+

Partial Catenary 10- 90% CFO

- Visible at the station and beyond depending on topography of the line
- Mature technology

+



Traction battery

- ○ Battery is a good solution for CFO applications due to the large amount of stored energy – long range.
- ○ Battery is cost effective for CFO.

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*Power Supply and Distribution

primove *Rail*
Questions & Answers

Question #2: PS&D, mixed catenary & CFO operation

More details:

With a battery pack, the key is to keep the discharge depth to a minimum to increase battery life

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primove *Rail*
Questions & Answers

Question #3: Winter operation: in-street conductor, salt, corrosion, and snowplows

Winter operation in Augsburg Germany

In-street primove cabling is sealed beneath asphalt - based wear material.

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primove *Rail*
Questions & Answers

Question #4: Has the in-street conductor been installed in mixed use traffic lanes? Has it been installed in reserved lanes with normal traffic operating at right angles across it? Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

Bombardier's primove system is not based on in-ground conductor technology but on in-ground inductive power transfer technology. As such, the power transfer elements are buried in the ground and sealed off from the elements, providing a system entirely immune from the weather, rubber tire, oils, autumn leaves, etc…

Wear testing of the in-ground wear component is underway at an independent test lab in Europe, simulating traffic conditions on an intermediate highway. We are 4 months into six months of the 10-year (equivalent) test with no damage visible.

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primove *Rail*
Questions & Answers

Question #5: In-street conductor, turnouts, crossings, vertical curves, clearances to adjacent steel items

Gaps can be left where necessary for continuous primove, this is not an issue for partial primove or catenary/battery. Steel items under the tracks are not affected because primove naturally shields them.

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primove *Rail*
Questions & Answers

Question #6: Batteries: type, vehicle acceleration & speed

Vehicle performance is identical to catenary operation (acceleration typically limited by customer specification). The maximum design speed of the vehicle is 80 km/h

Bombardier is using Li-Iion cells widely used in automotive and military applications, manufactured by one of the biggest battery manufacturers.

Bombardier is using a similar system on a prototype bus system running in the Mannheim area.

Our overall activities in energy storage technologies for CFO operation is longer than 10 years, with several prototypes in long term operation. We have 19 vehicles with onboard energy storage based on double layer capacitors running in daily commercial operation since 2009.

The system concept for CFO operation with Li-Ion battery system is based on this experience with more then 5 million km travel distance

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Questions & Answers

Question #7: Battery operation: What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third-party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

Bombardier prefers to discharge to 50% and charge to 80% in normal operation to maximise the battery life and maintain reserve power. Further discharge is possible occasionally and complete charge is delivered at locations where there are long stops.

The battery management system is provided by the battery supplier. Each cell voltage is monitored and temperature is also monitored in several places in the module.

The battery module and monitoring system are modularised for effective supervision and redundancy.

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primove *Rail*
Questions & Answers

Question #8: The operating environment in DC has a temperature range of -15^{0}F to 106^{0}F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

The system is designed for operation in ambient temperature from -20 to +110°F.

Bombardier utilizes design and a thermal management system to optimize battery function, especially at temperature extremes.

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primove *Rail*
Questions & Answers

Question #9: There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

The batteries are located on the roof of the vehicle and are not susceptible to impacts in traffic accidents.

The Bombardier system is more robustly designed than the system in the Chevy Volt, and our standard procedure is to drain the battery after an incident.

The Chevy Volt incident was caused by when the battery system was not discharged after the crash (discharging reduces the reactive behavior of the battery system dramatically) and a hole caused by the accident allowed the heated battery cells to ignite the interior of the car.

Criteria have been established for shock and abuse from cell level to system level (e.g. nail penetration test on cell level and crush test on system level). In addition we have criteria for shock and vibration on a charged battery system corresponding to 30 years operation.

Validation activities are in progress.

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primove *Rail*
Questions & Answers

Question #10: If a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge?

What would be the maximum current draw for battery recharging?

Bombardier does not recommend to run 3 miles off wire on a 2% grade as today's battery technology does not allow a reasonable depth of discharge for such a power draw. Bombardier believes that battery life would be compromised by such operation.

The above statement also assumes that this operating scenario is also valid while using full HVAC.

In order to meet this demanding grade, the battery size would be such that it is likely the axle load of the vehicle would be exceeded.

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primove *Rail*
Questions & Answers

Question #11: If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106^{0}F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160^{0}F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

The largest issue is the contact shoe welding to the catenary in static charging. Special pantograph technology is required. Charging with primove does not have this issue, nor does dynamic charging from the catenary.

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primove *Rail*
Questions & Answers

Question #12: What is the time required to recharge fully depleted supercapacitors at a stop? What level of current and voltage is this time based on?

The supercaps take less than 30 seconds to charge from fully discharged. In normal operation the discharge would be limited to extend the supercap life so typically 15 second charge time. The vehicle bus is nominally 750 VDC.

Bombardier does not recommend supercaps for extended CFO operation.

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primove *Rail*
Questions & Answers

Question #13: For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

For this application catenary charging of on-board energy storage is recommended.

However discrete primove charging segments at stations and critical locations is also a good choice.

The PS&D layout will depend on the alignment and grid connections available.

A/C voltage from the local medium-voltage grid supply can be accommodated, or from the transit system DC supply.

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primove *Rail*
Questions & Answers

Question #14: If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

Bombardier's recommended maximum distance while running on battery and full HVAC is about 2 km on level track (segregated right of way also recommended). Primove segments can be installed on extended grades to ensure no issues with battery depletion.

Please supply the alignment details and we can provide analysis and recommendations for the optimum CFO solution.

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primove *Rail*
Questions & Answers

Question #15: Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Bombardier is sizing the batteries such that their life is not compromised. This means that there is still energy in the batteries that can be used on CFO portions of the line should the vehicle get stuck in traffic.

In the case of extended delays the preferred scenario is to enter into load shedding modes according to a pre-determined sequence of events such as 100% HVAC to 50 % HVAC to Ventilation.

In the very unlikely event that a vehicle does get stranded then normal vehicle recovery techniques will be employed.

Primove charging segments can be installed in high congestion areas to mitigate any risk.

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primove *Rail*
Questions & Answers

Question #16: The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

The consequences of using a vehicle of that size and in particular the narrow width is that this infringes on the capability to adapt to higher ridership in the future as boarding stations will not accommodate a larger standard vehicle.

In order to preserve battery life and to be able to run in traffic with the likelihood of being stuck in traffic in a CFO portion of the line, a small 2.4 x 20 m streetcar is incompatible with the required battery size as it lacks the space and axle load carrying capacity of the larger vehicle.

Bombardier normally bases its CFO offering on a vehicle that is of the following size:
2.65 m x 30 m bi directional

This allows for the battery to be installed on the roof of sufficient capacity.

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primove *Rail*
Questions & Answers

Question #17: The District’s current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

As per question 16, Bombardier is recommending a 2.65 m x 30 m long vehicle

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primove *Rail*
Questions & Answers

Question #18: The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

To be discussed at the meeting.

Difficulties:

1. Roof & undercar layout
2. Electrical interface
3. Propulsion – may need to retrofit
4. Axle load

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primove *Rail*
Questions & Answers

Question #19: What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

Standard equipment: Battery tester, hi-pot

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Questions & Answers

Question #20: Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?

Operational training is required, as is training for maintenance personnel on HV battery maintenance and safety. Bombardier recommends that qualified technicians perform all LRV maintenance.

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the evolution of mobility

http://primove.bombardier.com

Brookville

BROOKVILLE

Brookville is ...

A WORLD CLASS AMERICAN MANUFACTURER

Question #1

The District will consider designs which allow for the use of an in-street conductor which supplies power to the vehicle continuously while operating, a system with long gaps in the overhead supply and wired areas for recharging while operating (batteries), or a system which charges an on-board storage system only when stopped at station platforms (supercapacitors or flywheels). Which of these types of systems have you supplied vehicles (rail, bus, or other transport) for? Or, are in the process of supplying? Do you have any comments on the advantages or disadvantages concerning the three system types?

Response

We currently have supplied rail vehicles with on-board ESS battery systems. The ESS systems have been charged by overhead wire, or by non-contact inductive transfer charging. We are currently in the process of supplying a lithium-ion ESS solution to the city of Dallas in a Modern Streetcar. The current Dallas alignment has a 1 mile off-wire section, with total system length of 1.6 miles.

- Supercaps advantage gives you a higher power output for short duration accelerations compared to a battery solution. Supercaps recoup braking energy more efficiently than battery, and charge at higher rates. They have a higher cost per kwh and lower energy density.
- Batteries advantage give you a higher energy capability for longer duration off wire systems.
- Possible combination of super caps and batteries for a multiple start/stop wireless section. Areas of concern with combination are cost, space, and complexity.

Question #2

A traditional streetcar is designed to operate from an overhead supply system operating continuously at either 600 or 750 Vdc. Would your company's offering place any special or additional requirements concerning integration of the electrification system? Would your technology operate with a pantograph when not on a wireless section?

Response

We would not require any additional requirements from the electrification system. Our streetcar would operate with a pantograph when not on a wireless section.

Question #3 – In Street Conductor

Has the in-street conductor been utilized in areas which normally experience snow and ice in the winter? What material would you use for fabricating in-street conductors? Would the material show corrosion for the application of de-icing road salt? What provisions are made to prevent snow plow blades from damaging the rail?

Question #4 – In Street Conductor

Has the in-street conductor been installed in mixed use traffic lanes? Has it been installed in reserved lanes with normal traffic operating at right angles across it? Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

Question #5 – In Street Conductor

How is the conductor installed in the street? Are there any restrictions on horizontal or vertical curvature of the pavement? How are crossings or turnouts implemented with the conductor rail? What clearances are required for other structures such as manholes and metallic covers?

Response

Not Applicable. The current Liberty Streetcar ESS system does not utilize an In Street Conductor

Question #6 – Batteries

Which battery type do you have experience in applying, Lithium (Li) or Nickel Metal Hydride (NiMH)? What is the maximum acceleration rate and maximum speed normally used in these applications?

Response

We currently have experience with Lithium-Ion battery technology. Our current design utilizes a 2.0 mphps acceleration rate for weights between AW0 and AW2 for speeds between 0-15 mph on level tangent track. Maximum speed maybe limited.

Question #7 – Batteries

What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third-party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

Response

Although the Lithium-Ion Battery can discharge or charge at very high C-rates, we are limiting our battery to a maximum discharge rate of 4C-5C, and a charge rate of 1C. At higher discharge or charge rates the cells will produce more heat, which is detrimental to the overall life of the cell.

Question #8 – Batteries

The operating environment in DC has a temperature range of -15^{o}F to 106^{o}F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

Response

Our design utilizes a thermal management system which has the capability of heating or cooling the battery dependent upon the ambient/battery module temperatures.
High temperatures are detrimental to the batteries. The Lithium-Ion batteries optimal operating temperature range is from 85 F to 95 F.

Yes a thermal management system is provided with our battery solution.

Question #9 – Batteries

There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

Response

Due to the design of the Chevy Volt cooling system, in which coolant was in direct contact with the cells, the coolant leaked, crystallized, and shorted the cell which was the cause of the fire. Our thermal management system does not have the coolant in direct contact with the battery cell.

Our batteries are located undercar on the A/B end carbodies. The battery enclosure is centered under the carbody. A crash analysis is being performed to determine the need for impact protection to the ESS system.

The battery manufacturer impact/shock criteria, which are being incorporated into our ESS system design.

We have incorporated several design features which maximize the safety of the Lithium-Ion battery. For example we operate at a lower SOC, battery management system monitoring, high voltage disconnecting contactors, and battery module construction

Question #10 – Batteries

Batteries will be discharged during overhead gaps and recharged while operating in wired sections. As a "ball-park" approximation, if a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge? What would be the maximum current draw for battery recharging?

Response

Without specific alignment details, stop durations, speed, etc it is very difficult to determine the energy we would need for this specific scenario. However, making some "ballpark" assumptions we estimate the need to charge for 30-45 minutes to recharge the batteries keeping the 1C charge rate.

We would need approximately 133 amps from the overhead supply for battery recharging.

Question #11 – Batteries

If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106^{o}F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160^{o}F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

Response

Our pantograph is designed for a maximum stationary current of 200 amps. Our typical stationary current draw with maximum auxiliary power and battery charging will be approximately 150 amps.

If required, further investigation would have to be conducted with our pantograph supplier.

Question #12 – Supercapacitors

What is the time required to recharge fully depleted supercapitors at a stop? What level of current and voltage is this time based on?

Question #13 – Supercapacitors

For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

Question #14 – Supercapacitors

If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

Response

Not Applicable. The current Liberty Streetcar ESS does not have supercapacitors.

Question #15 – Batteries & Supercapacitors

Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Response

Utilizing the battery management system we constantly monitor the State of Charge (SOC) of the battery. Our vehicle controller will utilize this information to start shedding loads at predetermined setpoints thus minimizing the risk of the car being stranded on a section of unpowered rail. Also, acceleration and speed limits will be reduced at a predetermined SOC level to help conserve battery power.

The vehicle is provided with emergency stowable couplers that can be used to move the car to a powered section of rail.

Question #16 – Vehicle Design Criteria

The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

Response

The Liberty Streetcar is currently offered in two standard vehicle widths. The narrow 8 ft (2.46 m) vehicle and the 8 ft 8 in (2.65 m) vehicle.

Question #17 – Vehicle Design Criteria

The District's current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

Response

The Liberty Streetcar has a standard length of 66 ft which permits sufficient space for the mounting of our ESS solution.

Question #18 – Retrofit of Existing Vehicles

The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

Response

Due to the many unknowns of the existing vehicle structural designs, areas available for ESS components, and the integration of the ESS into the existing electrical systems we do not feel this is feasible.

Question #19 – Specialized Equipment

What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

Response

No specialized equipment is required to maintain our ESS system.

Depending upon if spare battery modules/pack are purchased an intelligent battery charger maybe required for maintenance during storage.

Special test and troubleshooting procedures will be provided for the ESS system. The ESS system has midpoint contactors that reduce the voltage for safe trouble shooting.

PPE will be required at a minimum may be rubber gloves and cotton clothing, etc.

Question #20 – Training and Education

Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?

Response

Additional training for vehicle maintainers and vehicle operators will be required.

Typical electrical technicians will be required to maintain the ESS system.

BROOKVILLE

Brookville is ...

A WORLD CLASS AMERICAN MANUFACTURER

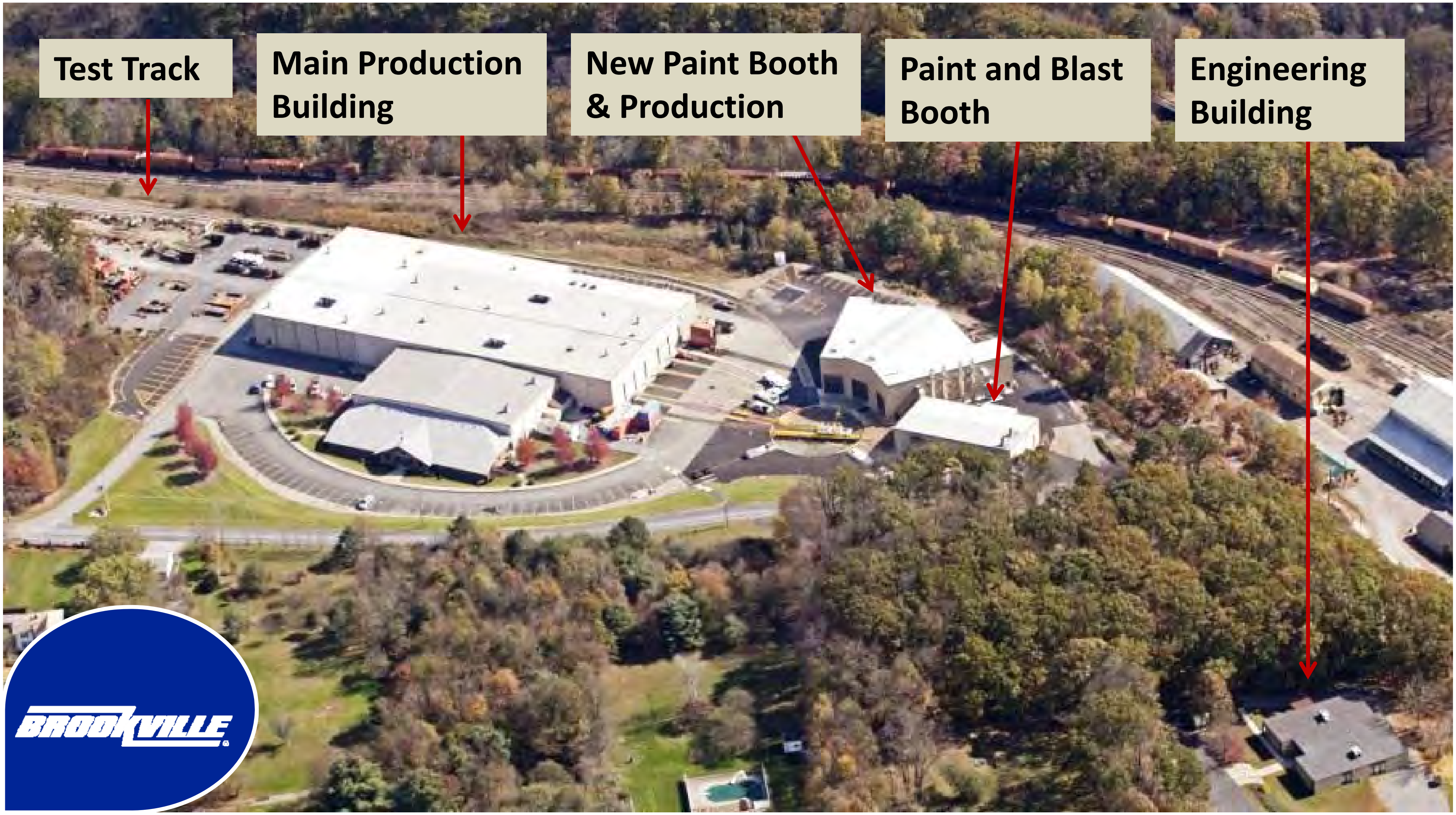
Brookville Equipment Corp.

- Founded in 1918
- OEM of rail vehicles
- Manufactured over 4,200 rail vehicles
- Produced 66 vehicles with Energy Storage Systems
- 68 Streetcars running in USA

1927 – 28 passenger rail bus

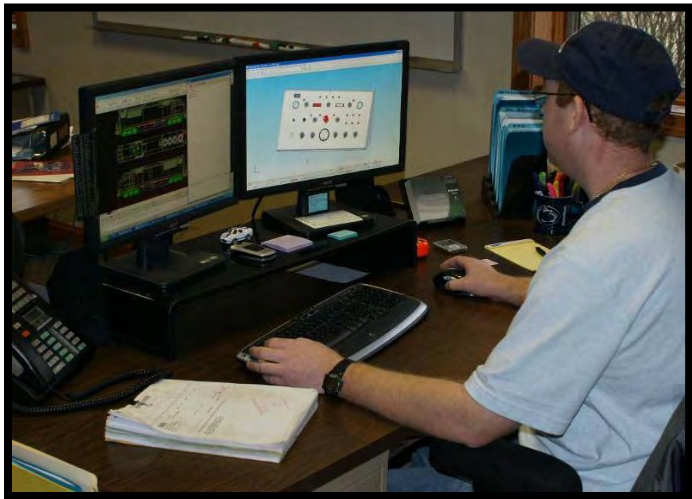
Main Production Facility

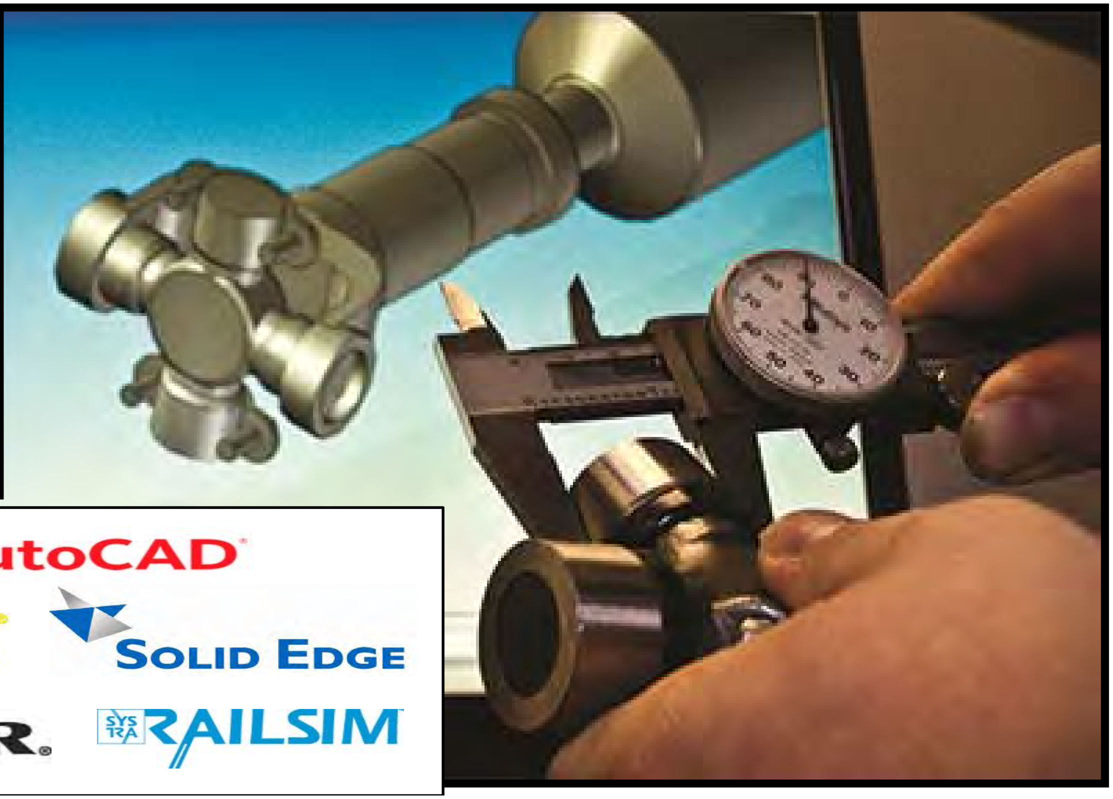
- Established American Manufacturing Since 1918
- Engineering, Design, Manufacturing, Testing and Service all located in single location



Unsurpassed Engineering & Design

- In-house Engineering and Design Departments
  - 5 : 1 Manufacturing to Technical Ratio
- Efficient and Controlled Engineering
- Innovations & Advancements: Multiple Patents
  - Trolley Pole Patent





AutoCAD

ANSYS

SOLID EDGE

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RAILSIM

BROOKVILLE

Markets for Rail Vehicles

Battery, Trolley & Diesel Mining & Tunneling Vehicles

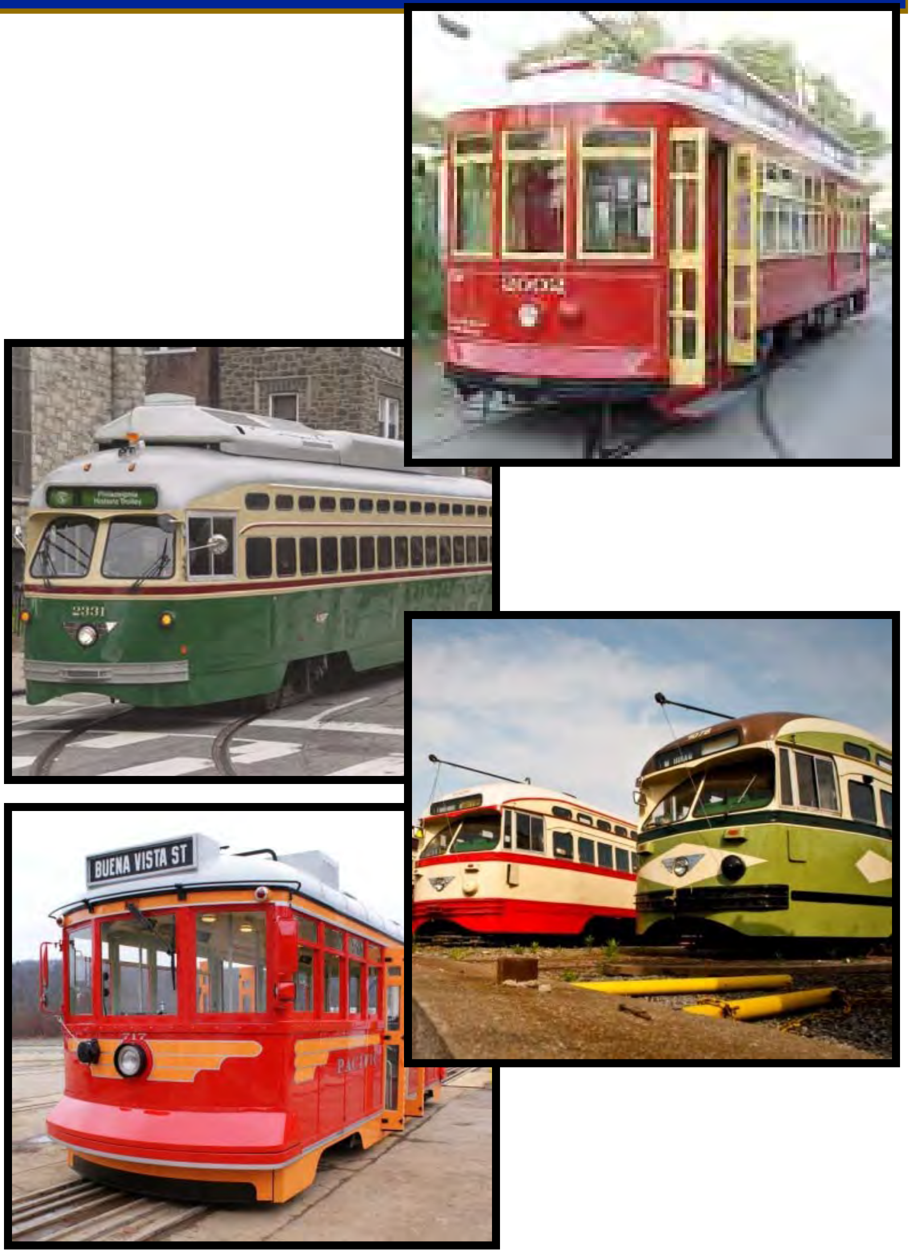
Streetcars

Passenger Locomotives

Freight Locomotives

Streetcar Projects

1. **New Orleans Transit Authority (NORTA)**
   - 31 streetcars
2. **Southeastern Pennsylvania Transportation Authority (SEPTA)**
   - 18 streetcars
3. **San Francisco Municipal Transportation Agency (SFMTA)**
   - 17 streetcars
4. **Walt Disney Corporation**
   - 2 streetcars



Proven History - Modern Systems, Subsystems and Components

Proven Historical Success

- IGBT AC and DC Propulsion Systems
- Regenerative and Dynamic Brake Systems
- Wireless Induction Charging Systems
- Dual Control
- Proven Soft-Ride Trucks
- Proven HVAC systems and ducting
- Collision Energy Management Systems

Proven Truck Design

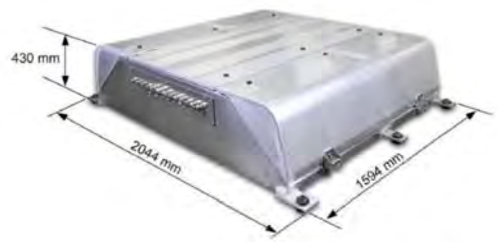
Modern Streetcar Truck

- 49 streetcars running in everyday revenue service starting in 2001
- Proven in service with AC and DC traction motors
- Improved ride quality
- Reduced noise
- Increased reliability

BROOKVILLE

Proven Propulsion & Control Systems

- ABB propulsion package is proven operationally on over 500 vehicles worldwide & in the USA
- Redundancy with ABB propulsion system
- TMV Control System is the latest in vehicle and traction control
- TMV Control System is proven on 31 streetcars in operation in USA since 2002
- User friendly touch screen display with remote diagnostics



Proven HVAC System

- Thermo King HVAC system proven on major systems throughout the USA (CTA, NYCT, Amtrak, etc)

- Thermo King LRV Unit is efficient, self-contained, low-profile, roof mounted unit

- 4.3 tons cooling & 10 kW overhead heating per unit
  - 3 units = 12.9 tons & 30 kW
  - 4 units = 17.2 tons & 40 kW

BROOKVILLE

Proven Carbody Manufacturing

- Manufacturing workforce expert craftsmanship of LRV carshells
- Highest manufacturing standards of ASTM, FRA, APTA, AWS
  - Qualified welding on corrosion resistant, carbon and stainless steels, and aluminum

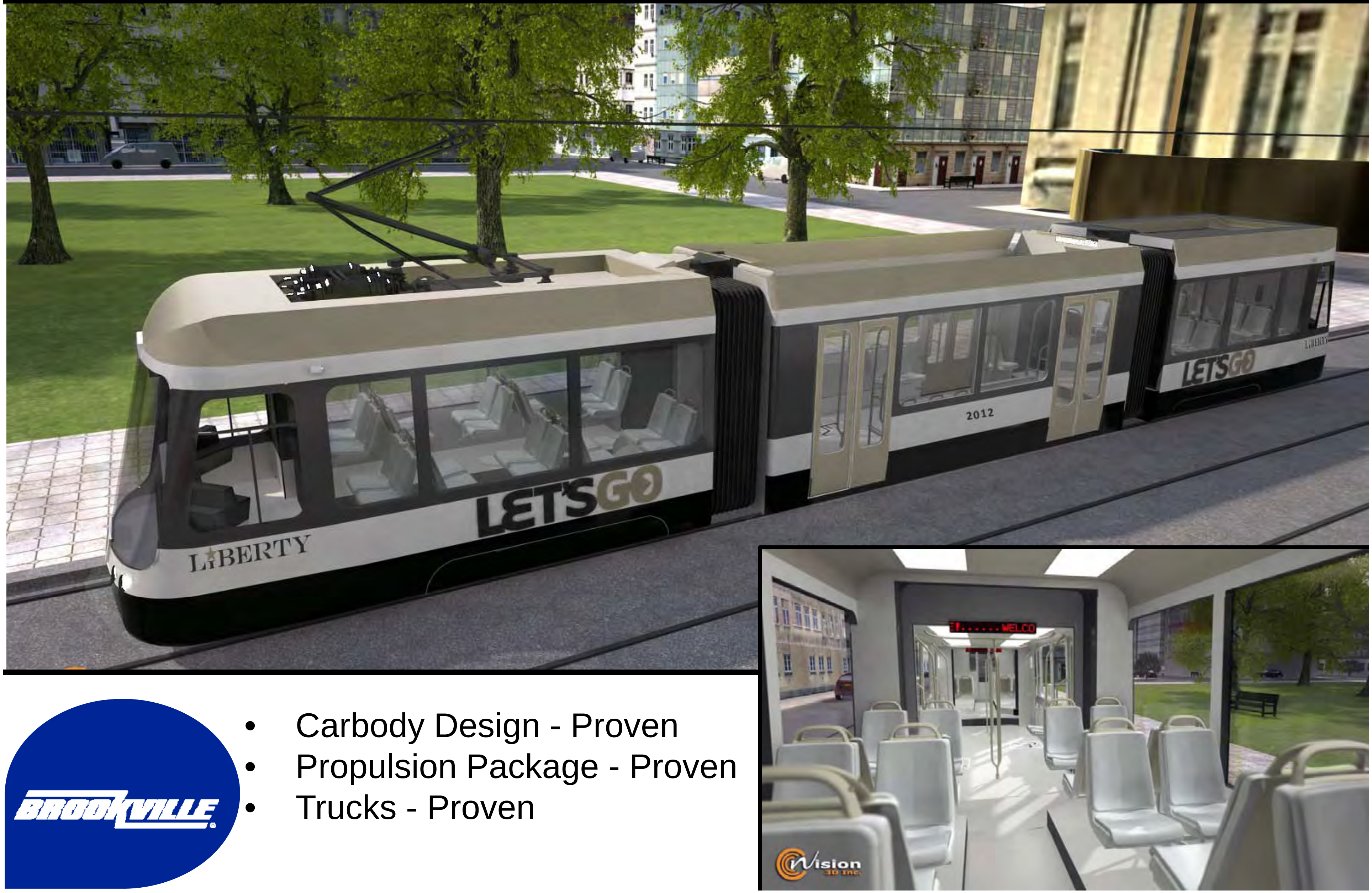
BROOKVILLE

Interior Fit and Finish

- History of Modern Interior Designs
- Known for attention to fit and finish details
- Passenger and Operator Ergonomics
- Lighting
- Passenger Comfort & Safety
- CFD analysis for HVAC

BROOKVILLE®

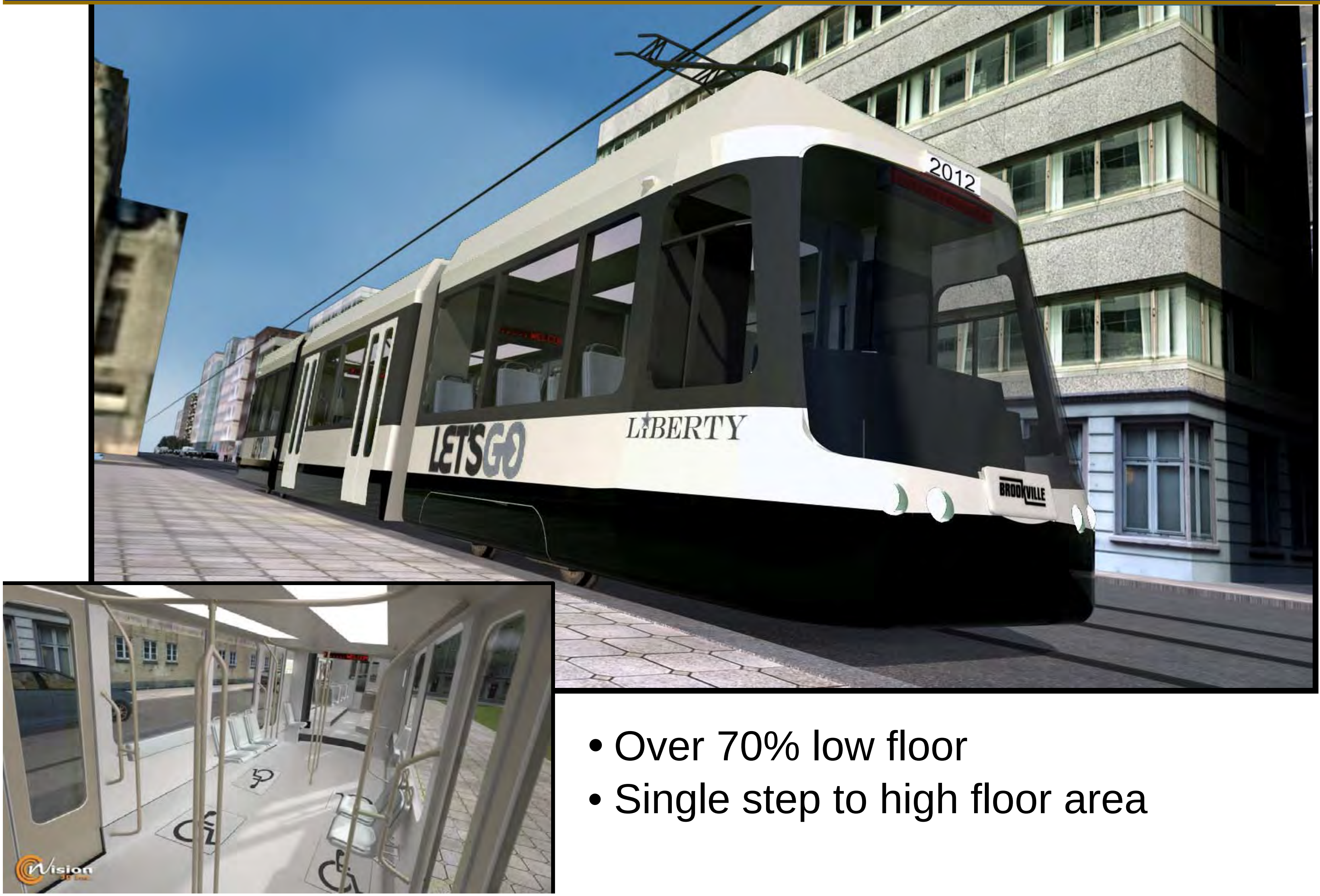
Liberty Streetcar



BROOKVILLE

- Carbody Design - Proven
- Propulsion Package - Proven
- Trucks - Proven

Liberty Streetcar



- Over 70% low floor
- Single step to high floor area

Customization Options

Regular Package Options

- Available in two body widths (8ft or 8ft 8in)
- Various Seating Arrangements
- Different Door Configurations
- Differing body trim and paint schemes
- Operators compartment configuration
- Bike Storage
- Fare box / payment system
- Pantograph

Standard Options

- Energy Storage System for off-wire operation
- Multiple Unit Operation

Dallas Streetcar Project

- Downtown Dallas to Oak Cliff
- Awarded in March, 2013
- Two Streetcars w/ Option of Two
- 8 Feet (2.46m) width vehicle
- ESS system for off-wire operation
- 1.5 mile line w/ 1 mile off-wire
- Delivery End of 2014

BROOKVILLE

Service & Support

- Dedicated Service Department
- Educational Operator & Maintenance Training
- On-site Field Engineer for Entire Warranty Period
- Remote Diagnostic Capabilities
- Various Extended Service Packages Available

LIFE CYCLE
MANAGEMENT

BROOKVILLE

What You Get With BROOKVILLE

- Unrivaled Engineering
- Established Skilled American Manufacturing
- All Under One Roof in One Location
- Proven Track Record
- **Customer Satisfaction is #1 Priority**
- **Partner - not just a supplier**

BROOKVILLE

Where commitment, quality, and experience combine to benefit the District of Columbia

Alternatives Analysis
Union Station - Georgetown

Supplier Questionnaire

April 3, 2013

Liberty Streetcar

BROOKVILLE®

Brookville Equipment Corporation (BROOKVILLE) is pleased to provide a response to the District of Columbia's Alternative Analysis for the introduction of premium transit service from Georgetown Waterfront to Union Station. We understand that sections of this alignment may limit the use of overhead wires and BROOKVILLE currently has a solution for situations such as this.

BROOKVILLE is currently engineering, designing, and manufacturing Modern Liberty Streetcars for the City of Dallas which are equipped with an onboard Energy Storage System (ESS) to allow the streetcar to operate for extended periods without the use of overhead wire. Please find responses to the questions provided below.

Question #1

The District will consider designs which allow for the use of an in-street conductor which supplies power to the vehicle continuously while operating, a system with long gaps in the overhead supply and wired areas for recharging while operating (batteries), or a system which charges an on-board storage system only when stopped at station platforms (supercapacitors or flywheels). Which of these types of systems have you supplied vehicles (rail, bus, or other transport) for? Or, are in the process of supplying? Do you have any comments on the advantages or disadvantages concerning the three system types?

Response

We currently have supplied rail vehicles with on-board ESS battery systems. The ESS systems have been charged by overhead wire, or by non-contact inductive transfer charging. We are currently in the process of supplying a lithium-ion ESS solution to the city of Dallas in a Modern Streetcar. The current Dallas alignment has a 1 mile off-wire section, with total system length of 1.6 miles.

Supercaps advantage gives you a higher power output for short duration accelerations compared to a battery solution. Supercaps recoup braking energy more efficiently than battery, and charge at higher rates. They have a higher cost per kwh and lower energy density.

Batteries advantage gives you a higher energy capability for longer duration off wire systems.

Possible combination of super caps and batteries for a multiple start/stop wireless section. Areas of concern with combination are cost, space, and complexity.

Question #2

A traditional streetcar is designed to operate from an overhead supply system operating continuously at either 600 or 750 Vdc. Would your company's offering place any special or additional requirements concerning integration of the electrification system? Would your technology operate with a pantograph when not on a wireless section?

Response

We would not require any additional requirements from the electrification system. Our streetcar would operate with a pantograph when not on a wireless section.

Question #3 – In Street Conductor

Has the in-street conductor been utilized in areas which normally experience snow and ice in the winter? What material would you use for fabricating in-street conductors? Would the material show corrosion for the application of de-icing road salt? What provisions are made to prevent snow plow blades from damaging the rail?

Response

Not Applicable. The current Liberty Streetcar ESS system does not utilize an In Street Conductor.

Question #4 – In Street Conductor

Has the in-street conductor been installed in mixed use traffic lanes? Has it been installed in reserved lanes with normal traffic operating at right angles across it? Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

Response

Not Applicable. The current Liberty Streetcar ESS system does not utilize an In Street Conductor.

Question #5 – In Street Conductor

How is the conductor installed in the street? Are there any restrictions on horizontal or vertical curvature of the pavement? How are crossings or turnouts implemented with the conductor rail? What clearances are required for other structures such as manholes and metallic covers?

Response

Not Applicable. The current Liberty Streetcar ESS system does not utilize an In Street Conductor.

Question #6 – Batteries

Which battery type do you have experience in applying, Lithium (Li) or Nickel Metal Hydride (NiMH)? What is the maximum acceleration rate and maximum speed normally used in these applications?

Response

We currently have experience with Lithium-Ion battery technology. Our current design utilizes a 2.0 mphps acceleration rate for weights between AW0 and AW2 for speeds between 0-15 mph on level tangent track. Maximum speed maybe limited.

Question #7 – Batteries

What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third-party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

Response

Although the Lithium-Ion Battery can discharge or charge at very high C-rates, we are limiting our battery to a maximum discharge rate of 4C-5C, and a charge rate of 1C. At higher discharge or charge rates the cells will produce more heat, which is detrimental to the overall life of the cell.

Question #8 – Batteries

The operating environment in DC has a temperature range of -15 ^{0}F to 106 ^{0}F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

Response

Our design utilizes a thermal management system which has the capability of heating or cooling the battery dependent upon the ambient/battery module temperatures.

High temperatures are detrimental to the batteries. The Lithium-Ion batteries optimal operating temperature range is from 85 F to 95 F.

Yes a thermal management system is provided with our battery solution

Question #9 – Batteries

There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

Response

Due to the design of the Chevy Volt cooling system, in which coolant was in direct contact with the cells, the coolant leaked, crystallized, and shorted the cell which was the cause of the fire. Our thermal management system does not have the coolant in direct contact with the battery cell.

Our batteries are located undercar on the A/B end carbodies. The battery enclosure is centered under the carbody. A crash analysis is being performed to determine the need for impact protection to the ESS system.

The battery manufacturer impact/shock criteria, which are being incorporated into our ESS system design.

We have incorporated several design features which maximize the safety of the Lithium-Ion battery. For example we operate at a lower SOC, battery management system monitoring, high voltage disconnecting contactors, and battery module construction

Question #10 – Batteries

Batteries will be discharged during overhead gaps and recharged while operating in wired sections. As a “ball-park” approximation, if a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge? What would be the maximum current draw for battery recharging?

Response

Without specific alignment details, stop durations, speed, etc it is very difficult to determine the energy we would need for this specific scenario. However, making some “ballpark” assumptions we estimate the need to charge for 30-45 minutes to recharge the batteries keeping the 1C charge rate.

We would need approximately 133 amps from the overhead supply for battery recharging.

Question #11 – Batteries

If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106 °F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160 °F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

Response

Our pantograph is designed for a maximum stationary current of 200 amps. Our typical stationary current draw with maximum auxiliary power and battery charging will be approximately 150 amps.
If required, further investigation would have to be conducted with our pantograph supplier.

Question #12 – Supercapacitors

What is the time required to recharge fully depleted supercapitors at a stop? What level of current and voltage is this time based on?

Response

Not Applicable. The current Liberty Streetcar ESS does not have supercapacitors.

Question #13 – Supercapacitors

For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

Response

Not Applicable. The current Liberty Streetcar ESS does not have supercapacitors.

Question #14 – Supercapacitors

If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

Response

Not Applicable. The current Liberty Streetcar ESS does not have supercapacitors.

Question #15 – Batteries & Supercapacitors

Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Response

Utilizing the battery management system we constantly monitor the State of Charge (SOC) of the battery. Our vehicle controller will utilize this information to start shedding loads at predetermined setpoints thus minimizing the risk of the car being stranded on a section of unpowered rail. Also, acceleration and speed limits will be reduced at a predetermined SOC level to help conserve battery power.
The vehicle is provided with emergency stowable couplers that can be used to move the car to a powered section of rail.

Question #16 – Vehicle Design Criteria

The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

Response

The Liberty Streetcar is currently offered in two standard vehicle widths. The narrow 8 ft (2.46 m) vehicle and the 8 ft 8 in (2.65 m) vehicle.

Question #17 – Vehicle Design Criteria

The District's current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

Response

The Liberty Streetcar has a standard length of 66 ft which permits sufficient space for the mounting of our ESS solution.

Question #18 – Retrofit of Existing Vehicles

The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

Response

Due to the many unknowns of the existing vehicle structural designs, areas available for ESS components, and the integration of the ESS into the existing electrical systems we do not feel this is feasible.

Question #19 – Specialized Equipment

What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

Response

No specialized equipment is required to maintain our ESS system.

Depending upon if spare battery modules/pack are purchased an intelligent battery charger maybe required for maintenance during storage.

Special test and troubleshooting procedures will be provided for the ESS system. The ESS system has midpoint contactors that reduce the voltage for safe trouble shooting.

PPE will be required at a minimum may be rubber gloves and cotton clothing, etc.

Question #20 – Training and Education

Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?

Response

Additional training for vehicle maintainers and vehicle operators will be required.

Typical electrical technicians will be required to maintain the ESS system.

BROOKVILLE®

LIBERTY
MODERN STREETCARS

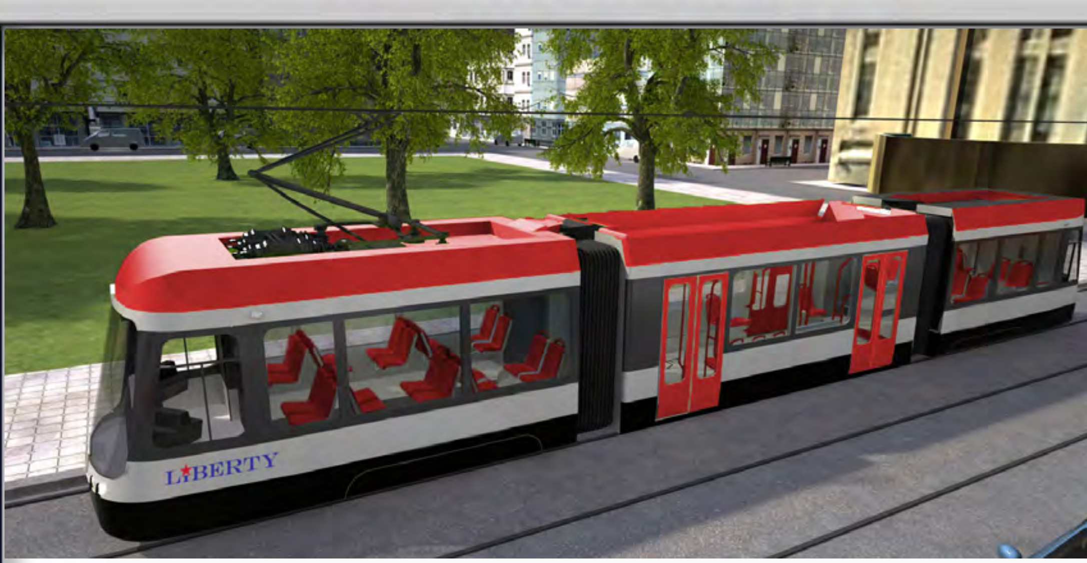
BROOKVILLE entered the streetcar market in 2002, contributing to the first truly "Made in USA" streetcars since the early 1950s. We currently have 68 streetcars in operation in the USA.

The Liberty Streetcar, BROOKVILLE's new light rail vehicle (LRV) platform, uses industry proven systems, sub-systems, and components. It was engineered after consulting operations and maintenance transit agencies to address streetcar industry needs. The car has been designed by an American workforce, using the best proven technology from around the world, and packaged for the North American market.

A Unique, Cost-Effective Solution: BROOKVILLE designs, constructs, and tests at a single location, permitting a convenient and cost-effective inspection schedule. Operations and maintenance training is included and conducted at your location by former transit agency professionals with hands-on experience. The Liberty Streetcar also takes FTA safety and security protocols seriously, and includes documents needed for inclusion in the Safety and Security Plan.

Our Customers Include:

- San Francisco Municipal Railway (SFMTA)
- New Orleans Regional Transit Authority (NORTA)
- Southeastern Pennsylvania Transportation Authority (SEPTA)



Above: Liberty Streetcar with three passenger compartments.

Left:
Interior of Liberty Streetcar with customizable seating arrangements.

Right:
Interior of Liberty Streetcar with just a single step to high-floor section.

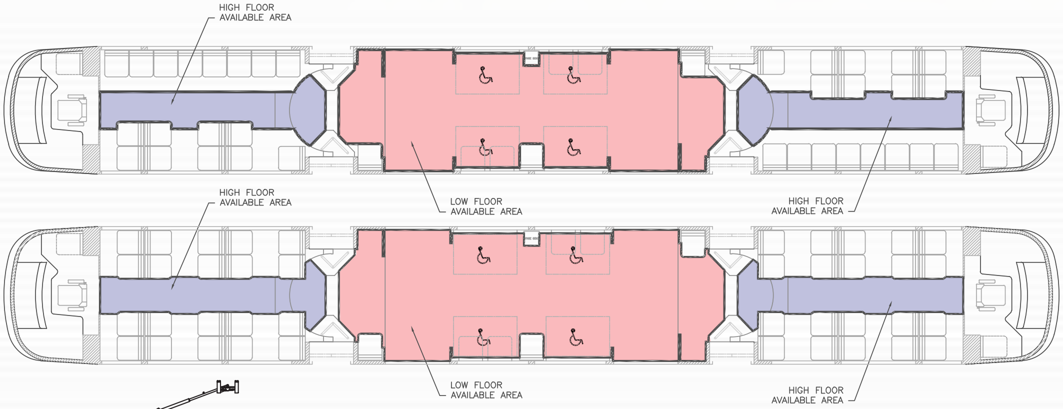
Left:
Exterior of Liberty Streetcar with sleek, modern design.

On Track for the ENVIRONMENT

INNOVATIVE SOLUTIONS FOR MODERN STREETCARS

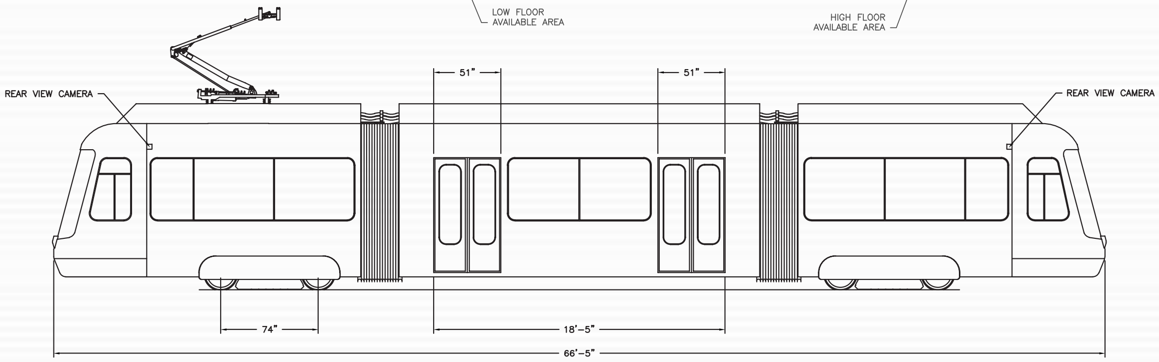
LIBERTY

Proposed Floor Plans Below Are Customizable For Your Specific Needs


HIGH FLOOR AVAILABLE AREA
LOW FLOOR AVAILABLE AREA
HIGH FLOOR AVAILABLE AREA
HIGH FLOOR AVAILABLE AREA
LOW FLOOR AVAILABLE AREA
HIGH FLOOR AVAILABLE AREA

Car Width
8 Feet
(2.45 meters)

Car Width
8 Feet, 8 Inches
(2.65 meters)



Smartphone Users: Scan this QR Code for more information on our Modern Streetcars.

Liberty Class Streetcar - Technical Specifications

Track Gauge	Standard 4 Feet, 8.5 Inches	
Boarding Height	13.75 Inches (350mm)	
Power Supply	750 V DC (Max. 925 V DC, Min. 525 V DC)	
Low-Voltage Power Supply	24 V DC	
Motors	4 x 65 kW or 4 x 99 kW	
Maximum Speed	44 mph (70 km/h)	
Minimum Turning Radius	59 Feet	
Vehicle Length	66 Feet, 5 Inches	
Max. Height (w/o Pantograph)	11 Feet	
Wheelbase	39 Feet	
Weight of Car Empty	63,960 lbs (without off-wire capability)	
Acceleration	3.0 mphps (1.3m/s2)	
Brake Deceleration	3.0 mphps	
Emergency Brake Deceleration	5.0 mphps	
Maximum Grade	9%	
Vehicle Width	8 Feet (2.46 m)	8 Feet, 8 Inches (2.65 m)
Percentage of Low-Floor Area	71%	73%
Total Seating Capacity	41 Passengers + 1 Operator	47 Passengers + 1 Operator
Maximum Capacity (AW3)	127 Standees + 41 Seated + 1 Operator = 169	135 Standees + 47 Seated + 1 Operator = 183
Maximum Capacity (AW4)	170 Standees + 41 Seated + 1 Operator = 212	181 Standees + 47 Seated + 1 Operator = 229

Features of the Car Include:

- Single step design between low floor and high floor sections
- Over 70% low floor
- BROOKVILLE soft-ride trucks proven under 49 streetcars in USA
- Meets Buy America requirements

Standard Options:

- Two body widths
- Different door configurations
- Various seating configurations
- Various body trim/paint schemes
- Multiple Unit operation (MU)
- Propulsion upgrades for higher speed
- Energy Storage System (ESS) for periods of off-wire operation

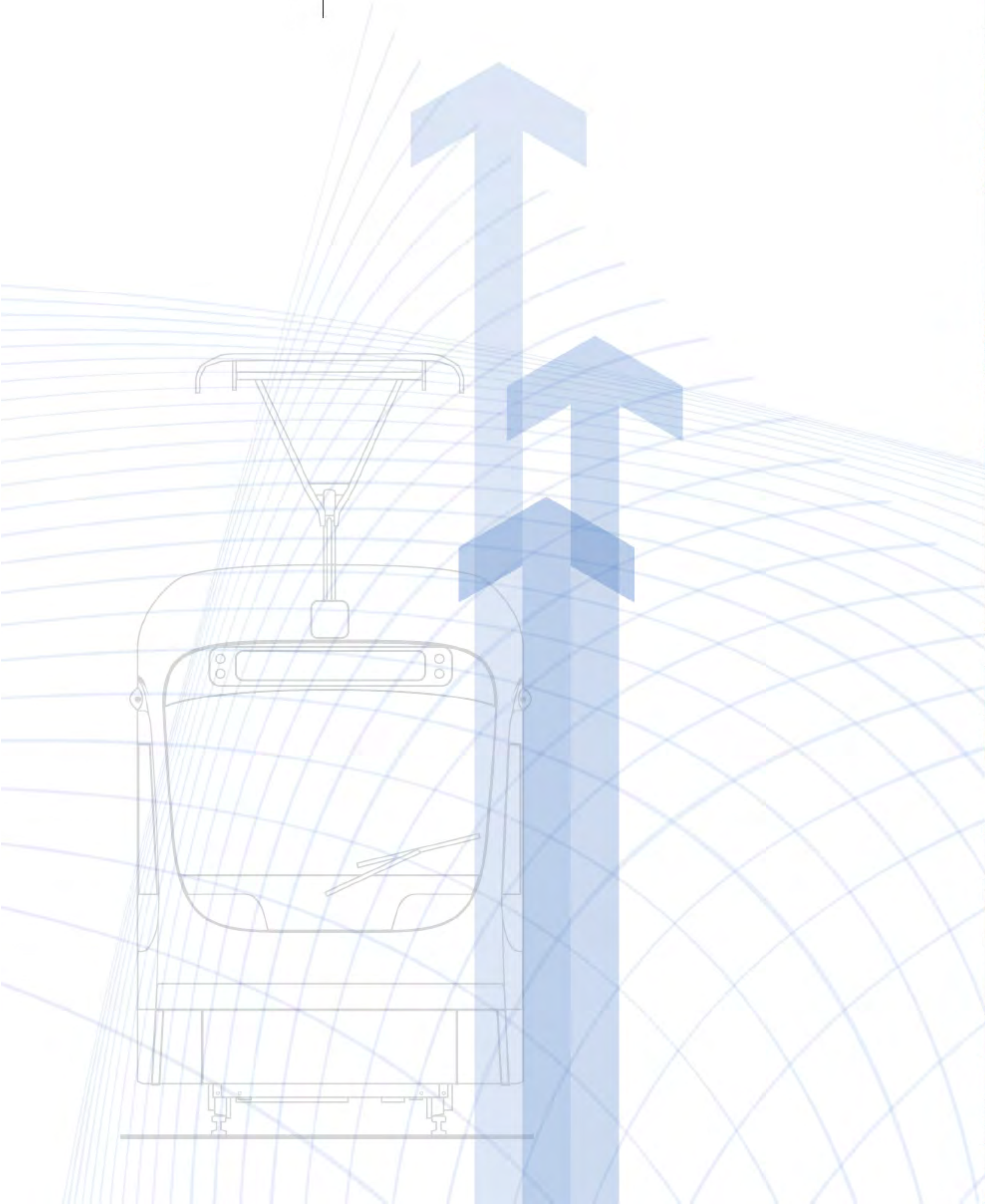
BROOKVILLE EQUIPMENT CORPORATION
175 Evans Street • Brookville, PA 15825 USA

WWW.BROOKVILLECORP.COM
Tel: 814.849.2000 • Fax: 814.849.2010

Kinkisharyo

Engineering
Sustainable
Urban
Transit

KINKISHARYO



beyond moving people

Who is KINKISHARYO?

KINKISHARYO has been customizing solutions for urban transit agencies worldwide for as long as there has been urban transit.

After designing and manufacturing more than ten thousand railcars, we continue to build on the heritage of technological innovation and customer service that have made us the number one supplier of low-floor light rail vehicles in North America. We know that each metropolitan area and transit system has needs beyond moving people safely and reliably. We tailor solutions to meet those needs.

From manufacturing to maintenance, from Dallas to Dubai, KINKISHARYO is delivering a full range of customer-focused, customized products and service that set us apart.

KINKISHARYO

Low Floor. Unlimited Ceiling.

high standards

About KINKISHARYO...

Policy

A Corporate Policy - A Customer Promise

Customer Focus
KINKISHARYO's long tradition of customization and innovation in vehicle design, outstanding manufacturing capabilities and maintenance proficiency provides our customers with the superior performance to meet their needs.

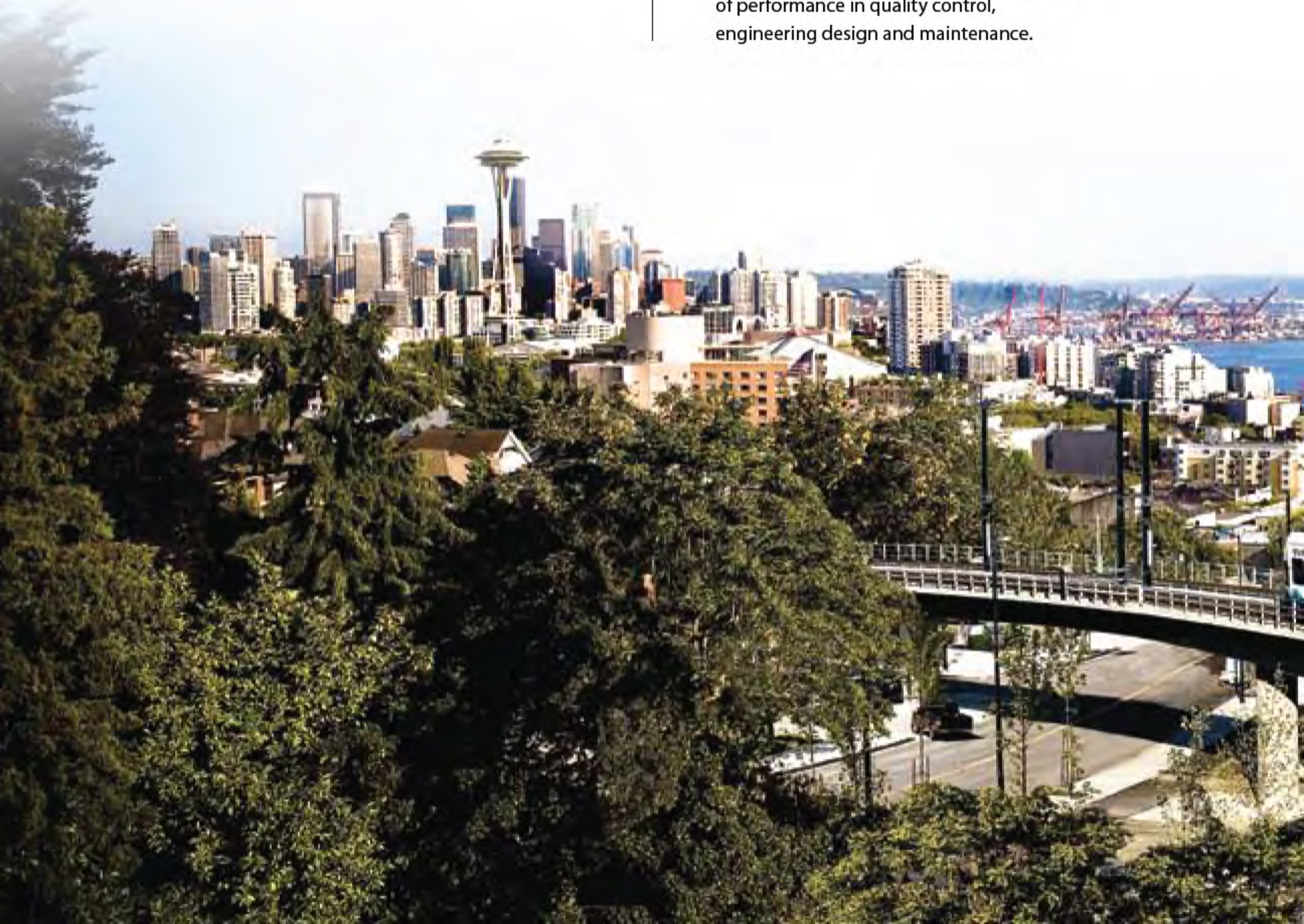
Our Mission
To provide high-quality products and services to our customers, on time and at a reasonable cost.

Strengths

Superior performance is why KINKISHARYO is the #1 manufacturer of low-floor light rail vehicles in North America.

Product Customization
Low-Floor LRV has evolved based on a standard platform.

Maintenance Proficiency
We apply the Kaizen principle of continuous improvement in every respect to all aspects of performance in quality control, engineering design and maintenance.



Technical Innovation

We're always finding new and better ways to enhance our rail cars. For example, we pioneered crashworthiness design, equipping cars with safety features like recessed couplers and energy-absorbent bumpers.

Safety & Reliability

Impeccable safety record -
Reliability as much as 6x the industry standard.

Long-Term Customer Relations

Your needs aren't static; they evolve over time. We design the solutions you need to keep pace.

Local Presence

When we come to a city, we invest in its economy by establishing local facilities and hiring & training a local workforce.

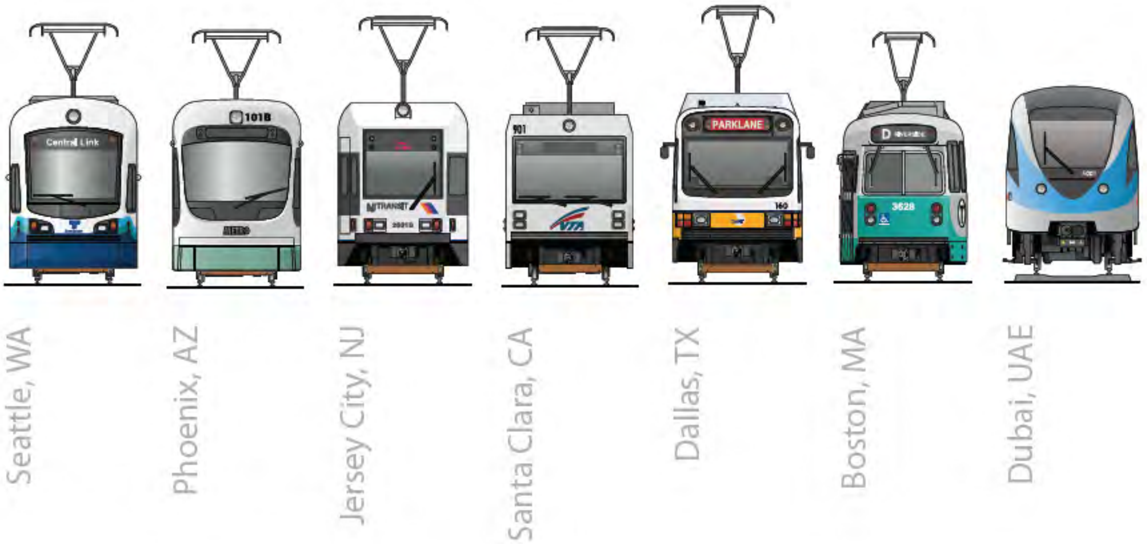
Career Development

We're committed to helping our dedicated employees progress professionally. Many of our maintenance workers, for instance, progress to management positions.

On Time, On Budget.

Because we keep our promise of on-time and on-budget performance, you can keep your promise of opening your system on time without burdening taxpayers with additional costs.

success stories
KINKISHARYO... Innovations

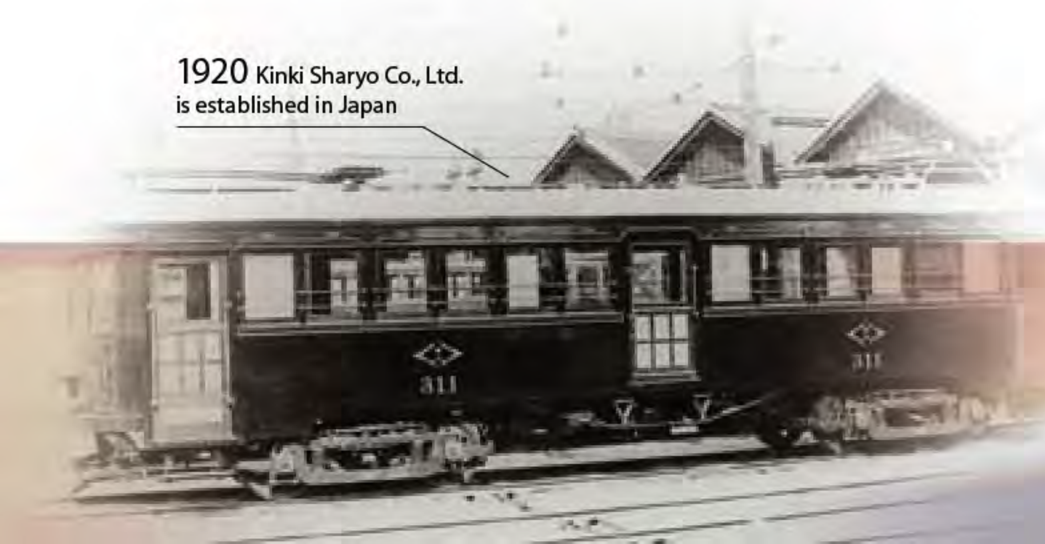


Unique challenges. One-of-a-kind solutions.

To get a true sense of KINKISHARYO, what makes us different and what we can do for you, start by taking a look at just a few of the places we've been... and how we've met the needs of cities and their transit authorities.

In each case, the project was as unique as the city and presented a completely new challenge. We succeeded every time because we listened to the client, understood their needs and developed a customized solution.

> KINKISHARYO is the #1 manufacturer of low-floor light rail vehicles in North America


1920 Kinki Sharyo Co., Ltd. is established in Japan

A History of Success

Explore our history of excellence in delivering innovative products.

success story DUBAI

world class transportation

Client: { **Dubai,**
United Arab Emirates

Challenge:
New urban rail system rivaling the luxury & comfort of a fine automobile

Solution:
Best in class, fully automated metro system for fast, efficient & safe transportation

The city of Dubai, located in The United Arab Emirates, is in the middle of an enormous construction boom intended to establish the city as the jewel of the Middle East. Every building and every project is designed to make a statement. So naturally, for their new urban rail system, Dubai demanded the finest metro vehicles in the world. And that's exactly what KINKISHARYO delivered: a fully-automated, world-class system for a world-class city.

> ...the finest metro vehicles in the world...

1980
The company produces its 10,000th electric rail car

1986
100 light rail vehicles delivered to MBTA, Boston

success story

SEATTLE

on time and on budget

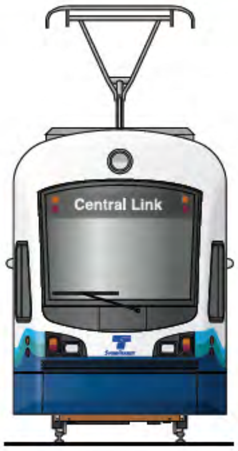
Client: { **Sound Transit**
Seattle, Washington • United States

Challenge:
Greener transit - on time & on budget

Solution:
62 environmentally-friendly, cost efficient low-floor vehicles

Seattle's Sound Transit was looking for more than just cleaner, greener railcars. They wanted a design that fit in with the vast beauty of the Pacific Northwest and matched the other vehicles in their transit fleet. But most critically, due to the high cost of operating a system in difficult terrain, they needed the cost efficient LRVs to be delivered on time and on budget.

KINKISHARYO met the challenge so well with the initial 35 low-floor vehicles, Seattle ordered an additional 27.



...delivered on time and on budget.
KINKISHARYO met the challenge...

1991
KINKISHARYO (USA), Inc. established in the U.S.

1999
KINKISHARYO International, L.L.C. established in North America

1995-2000
115 high-floor LRVs are delivered to DART, Dallas

success story
PHOENIX
safe and sleek success

Client: { **Valley Metro Rail**
Phoenix, Arizona • United States

Challenge:
Meet specific aesthetic and safety requirements

Solution:
Precise engineering, pioneering design

VMR asked us to develop safe light rail vehicles that could run in city streets with mixed traffic and to fit in aesthetically with the Phoenix area. It required precise human and industrial engineering at every stage of the design process.

To meet demanding safety requirements, we pioneered a crash energy management system that made us the very 1st car manufacturer to create a crashworthy low-floor LRV for North America.
With such features as recessed couplers and energy-absorbing bumpers, 50 of our custom-designed low-floor LRVs began service in 2008. They've proven their value by minimizing damage and injury in accidents.

...precise human and industrial engineering at every stage of the design process...

1997
20 additional LRVs are delivered to MBTA

1999 - 2003
Delivered 73 LRV's to NJ Transit, New Jersey

success story

JERSEY CITY

fast track to redevelopment

Client: { **NJ Transit • Hudson-Bergen Line**
Jersey City, New Jersey • United States

Challenge:
Rapidly increase passenger capacity, promote urban redevelopment

Solution:
DBOM Hudson-Bergen Line in 40 months

NJT needed to quickly add passenger capacity in a booming area near Manhattan. We responded by completing the project in an impressive 40 months from notice-to-proceed to in-service. The Hudson Bergen Line was the first Design-Build-Operate-Maintain (DBOM) transit operation in the U.S.

It was also the first in North America to feature a 70% low-floor light rail vehicle design. More than just moving people, it was about redeveloping an area where vacant brownfields once straddled the former Jersey Central line, which now stands a prosperous urban area thanks to the light rail.

...the first design-build-operate-maintain transit operation in the U.S...

2001
Delivered 100 LRV's to VTA, San Jose, CA

2006 - 2008
Delivered 50 LRV's to Valley Metro Rail, Phoenix

success story

SANTA CLARA

clean and environmentally friendly

Client: **Valley Transportation Authority**
Santa Clara, California • United States

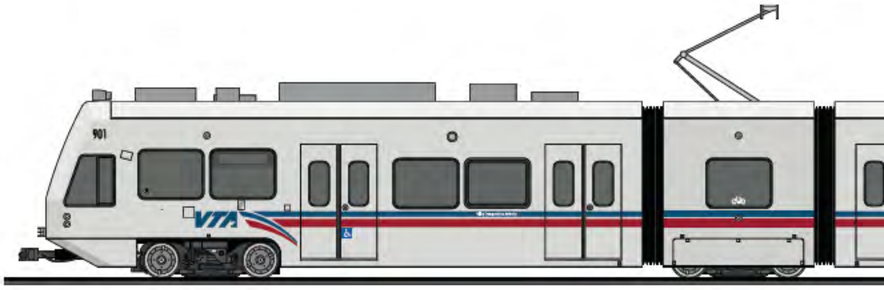
Challenge:
Expand & upgrade system to ease traffic congestion

Solution:
100 environmentally-friendly low-floor vehicles

The .com boom changed the landscape of California's Silicon Valley, bringing unprecedented prosperity, rapid growth... and traffic gridlock. With their public transit system straining to keep up with all this development, San Jose and Santa Clara County needed to quickly expand and upgrade.

KINKISHARYO designed and built 100 cars for the VTA to replace older fleet of step-well boarding cars with 70% low-floor direct platform-to-train boarding and interior bike racks. A fast, safe, environmentally friendly solution that's helping keep Santa Clara County moving in the right direction.

A fast, safe, environmentally friendly solution...



2008 - 2009
Delivered 35 LRV's to Sound Transit, Seattle

success story

DALLAS

customer commitment

Client: { **Dallas Area Rapid Transit (DART)**
Dallas, Texas • United States

Photo courtesy of DART

Challenge:

Increase capacity
enhance ADA
accessibility

Solution:

Innovative re-design
for long-term
customer

DART wanted to increase passenger capacity and enhance ADA accessibility without replacing existing cars or re-building platforms. This unique challenge called for an innovative solution: inserting new, custom-designed low-floor sections in the middle of their existing high-floor trains.

This innovation is known as the Super-LRV. The system opened in 1996 and continues to be one of the fastest-growing, most successful light rail systems in the country. And KINKISHARYO continues to play a major part in fueling the region's thriving economy.

This unique challenge called for an innovative solution...

TheSUPER-LRV

2008 - 2010
115 low-floor C-cars
delivered to DART

2010 - 2011
Delivered additional
48 SLRVs to DART

success story

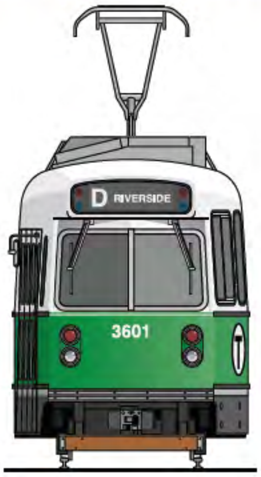
BOSTON

custom engineering - seamless integration

Client: { **Massachusetts Bay Transportation Authority (MBTA)**
Boston, Massachusetts • United States

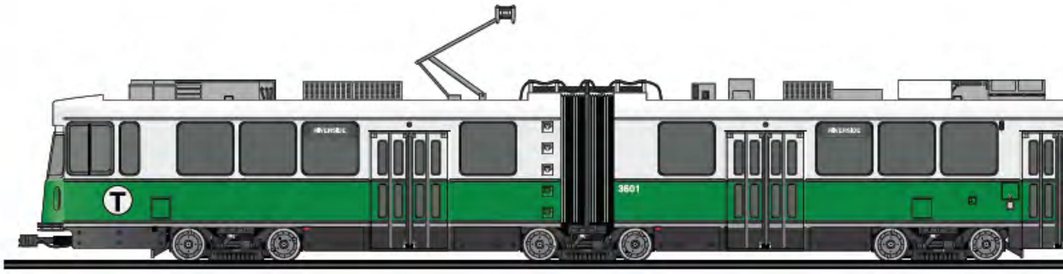
Challenge:
Century-old rail system

Solution:
Custom-designed vehicles to work with existing system



In 1983, Boston's Green Line was in need of a new, reliable light rail vehicle that could maneuver through the ice and snow of New England winters. They looked for a company that could modernize the line yet work seamlessly with the vehicles, signaling & communications systems already in place.

KINKISHARYO delivered 120 custom-designed and engineered high-floor light rail vehicles. The safety & reliability of the vehicles, keeping the residents and tourists moving quickly throughout Boston, has been the key to MBTA's success.



2010 - 2011
Delivered additional 27 LRVs to Sound Transit

2011
ameriTRAM™ streetcar unveiled.
www.ameritram.com

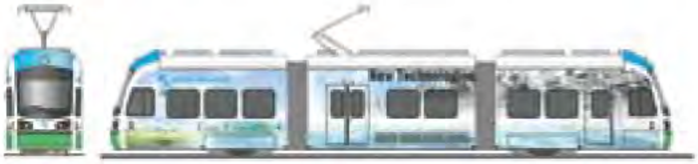
Our Vehicles

Metro

A rapid transit, subway or metro system is an electric public rail transportation system in an urban area with high capacity and frequency. Metros operate on dedicated right-of-way using underground, elevated or at-grade railway. Metros operate as multi-car trainsets or electric multiple units (EMU) with train length passenger access between cars. Modern metros are fully automated and driverless.

Features:
- High Passenger Capacity
- Grade Separation from Other traffic
- Fully Automated Driverless

Benefits:
- Meets Large Urban Area Transport Demands
- Higher Speeds, Faster Travel Times
- Safer, More Reliable; Lower Overhead Costs



Streetcar

A streetcar is a railcar of lighter weight and construction and slower top speed than an LRT Vehicle. It is designed exclusively for the transport of passengers within towns or cities, on tracks running primarily on streets. It is a 100% Low Floor configuration for exceptional passenger loading and unloading limiting dwell time in stations. Streetcars are most suitable for mixed traffic operations because of their size and speed.

Features:
- Full Width Cabs
- DOT Lighting
- 100% Low Floor Boarding
- Single Car Unit
- Light Weight and Smaller Size

Benefits:
- Designed For Mixed Traffic in City Streets
- Safe Design For Integration with Auto Traffic
- Very Rapid Passenger Loading & Unloading
- High Frequency Operations
- Low Power Consumption

A Vehicle Comparison: Metro • Streetcar • Light Rail

Light Rail Vehicle (LRV)

Light Rail is an electric rail transit system in an urban and suburban area that generally has capacity and speed between metro and streetcar systems. Light Rail is a versatile mode of rail transit suited for both dedicated right-of-way and mixed with traffic in city streets. LRVs are articulated units with low floor boarding areas for rapid loading and unloading of passengers at street level. LRVs are configured to operate as single units or up to four car trains.

Features:

- Highway Speed Capability
- DOT Lighting
- Low Floor Boarding
- Single or Multiple Units

Benefits:

- Right-Of-Way Versatility
- Safe Operation in Mixed Traffic
- Rapid Passenger Loading and Unloading
- Easily Adjustable Train Size for Peak Periods

The ameriTRAM™ Streetcar & DART Super Light Rail Vehicle

continuous improvement

Kaizen Approach

Vehicle Maintenance

When we come to a city, we hire and train a local workforce. We always aim to assemble the light rail vehicles locally, investing in the local economy and supporting regional growth. The same trained workers who built the vehicles then apply their accumulated expertise to servicing the cars and maintaining fleet performance.

At KINKISHARYO, we only maintain vehicles that we've designed and manufactured. For us, maintenance isn't just a service, but a product that compliments our core business, vehicle manufacturing. We focus on the big picture: the entire process, not just specific results. It's an approach called "Kaizen."

Kaizen and the Art of Vehicle Maintenance

"Kaizen" roughly translates to "continuous improvement in every respect." Our comprehensive approach to vehicle maintenance implements the Kaizen principle that no matter how well you're doing, you can always do better. We focus on improving the entire process, not just achieving certain results. We ensure continual improvement by applying innovation and analyzing all aspects of performance through management, engineering and quality perspectives.

Our approach to Kaizen has earned accolades from Federal Transit Administration auditors and peer groups for performance far above transit industry standards.

Process

KINKISHARYO provides our customers with a complete maintenance product including:

Features	Benefits
Engineered Maintenance Enhancements	Reduces repetitive labor costs and extends component service life
Failure Review Management	Analyze the effects of service failures for passenger impact, vehicle down-time, parts costs and fleet performance
Comprehensive Preventive Maintenance Programs: OEM requirements vs. actual in-service experience	Maximize Fleet Reliability & Availability
On-site Component Management	In-house repair, overhaul and functional testing
Progressively expanding planned maintenance	Reduces costs and vehicle down-time during major overhaul
Fully Integrated Maintenance Management Information System (MMIS)	Customized reporting of performance benchmarks and indicators
Use of bio-degradable cleaning products	Responsibly Green

Performance

Reliability & availability are the measures of a quality vehicle fleet and superior fleet maintenance operations. KINKISHARYO understands how to achieve both as the only manufacturer to design build and maintain fleets of LRVs in North America.

Notes:

Contact Us

KINKISHARYO International, LLC
400 Blue Hill Drive
Suite#3B
Westwood, MA 02090
Phone: 1.888.4.SHARYO • 1.888.474.2796
Web: www.kinkisharyo.com

E-mail: BusinessDevelopment@Kinkisharyo.com

Business Opportunities

We are always looking for talented manufacturers to deliver the quality products our vehicle designs demand. We look forward to developing relationships with companies that share the same commitment to superior product quality and 100% on-time delivery. We strongly encourage participation of all Disadvantaged Business Enterprises.

KINKISHARYO is an equal opportunity employer.

KINKISHARYO

KINKISHARYO International, LLC

U.S. Headquarters:

400 Blue Hill Drive
Suite#3B
Westwood, MA 02090
Phone: 1.888.4.SHARYO • 1.888.474.2796
E-mail: BusinessDevelopment@Kinkisharyo.com
Web: www.kinkisharyo.com

2012

Wireless
Streetcar Systems
Estimated Cost Savings

20 April 2011

Russo & Redd Consulting Group LLC
Innovative Program Management Solutions

Wireless Streetcar Systems

The age of wireless streetcars has arrived. Recent advancements in battery technology have made the dream of wireless systems a reality. Storage devices are smaller, smarter and more efficient than ever before. They fit easily into modern streetcar shells and work seamlessly with the car's other systems. Car frames, trucks, motors, doors, heating and air conditioning systems remain unchanged. Pantographs and power routing systems can be totally eliminated in small systems and optimized in larger systems. And the only new addition is the battery management system. This seamless evolution in power supply provides a number of improvements while preserving the proven performance of time tested systems.

Wireless technology is most suitable for streetcar systems up to 5 miles in length, or where constraints like historic district restrictions must be considered. They are safer, cheaper to build, cheaper to operate, aesthetically more pleasing and have less environmental impact. And construction is faster and less disruptive. Wireless systems minimize property requirements, nearly eliminate the cost of electrical infrastructure, reduce the cost of bridges and tunnels, shorten construction schedules, reduce construction impacts, reduce maintenance costs, improve safety, and improve yard and shop operations. The result is a system that delivers all of the advantages of a modern streetcar without the complications and traditional clutter of poles and wires. Some of the advantages of wireless streetcar systems are:

Property: Assembling the right of way for new streetcar system is a difficult proposition. Property is always at a premium. New lines are often built in abandoned or underused freight rail corridors that were originally constructed with narrow track centers and little, if any, room for expansion. Squeezing in a modern streetcar line, complete with catenary poles and duct banks for power distribution, becomes problematic and expensive. It is not uncommon for the right of way to cost more than $2M per mile.

Pole & wire clutter in urban environment

Urban environments are even more difficult, especially in older, densely developed neighborhoods where the streets and sidewalks are narrow. Catenary poles must either occupy space between the tracks, adding as much as 3' to the width of the track system, or they must be located on narrow sidewalks where they take up precious pedestrian space and add to the urban clutter of poles. Eliminating wires and poles enhances the prospects of neighborhood acceptance and reduces the cost and time required for environmental clearance. Catenary systems also require power distribution cables and negative return cables. That means a considerable amount of street excavation to build the duct banks, and it adds significant cost, time, and construction impacts to already expensive projects.

Traction power substation

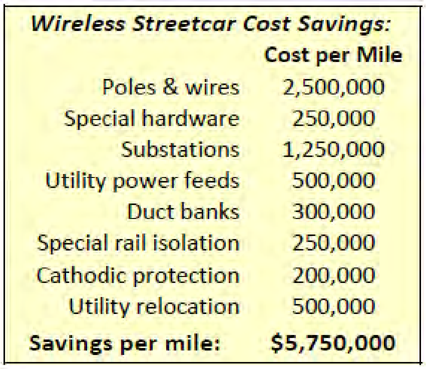
Locating substations is a particularly difficult property issue. Streetcar systems need substations about every mile. Typically, the substation footprint is about 1,000 SF. In an urban setting, that means finding an empty lot, locating them in a park, or purchasing existing commercial or residential property and converting it to an industrial application. Needless to say, this is a difficult and expensive proposition and generally meets with considerable resistance from the neighborhood, especially in a residential area. Even in an ideal setting, the underlying substation property could cost more than $500K. Substations also need power from the local electric utility. These are generally new underground cables that also add to the cost and impact of construction.

Power Infrastructure: The savings associated with wireless technology are substantial. Overhead catenary systems are expensive. Wireless technology eliminates all of the infrastructure and hardware associated with the distribution of power. It also eliminates the long term problems of stray current, and the cost of cathodic protection for underground utilities. At a minimum, wireless streetcar technology will eliminate:

- Overhead wires
- Line poles
- Tie offs and guy wires at curves
- Tensioning devices
- Sectionalizing switches and associated hardware
- Substations and substation feeds
- Power distribution and negative return cables
- Cathodic protection for buried utilities
- Utility relocation associated with underground construction
- Electrical isolation of the rail

Duct bank construction

The cost of catenary systems in an urban environment is typically about $2.5M per mile. That includes the poles, pole foundations, wires, and hardware. Tie-offs, guy wires, tensioning devices and sectionalizing switches adds another 10%, or $250,000 per mile. The average cost of a substation is approximately $1.25M and they are located about every mile. And the average cost of a utility feed to each substation can be taken as $500,000. The excavation and duct bank construction associated with the power distribution will cost, on average, $300,000 per mile. A major problem with "wired" systems is stray current and the resulting damage to buried utilities. Controlling stray current requires that the rails are wrapped in a special insulating material called a "boot". This is a laborious and costly element of work that is necessary to control stray currents. Wireless technology eliminates the need to "boot" the rail. Eliminating this element of work will save approximately $250,000 per mile. Stray current is also controlled through cathodic protection. Cathodic protection employs a suite of electrical devices attached to adjacent utilities and structures to counteract the effects of stray current. It is difficult to assign a cost to cathodic protection as it varies greatly from project to project. However, the cost can be substantial and it is reasonable to assign an average cost of $200,000 per mile. Lastly, utility relocation associated with the construction of the power distribution duct banks, substations, and catenary pole foundations will add another $500,000 per mile. Taken together, the capital cost savings of wireless technology is approximately $5.75M per mile. For a short urban circulator approximately 5 miles long, the total savings in capital costs is nearly $29M. These savings are substantial, and could offset nearly 100% of the cost of the vehicle fleet.



Wireless Streetcar Cost Savings:

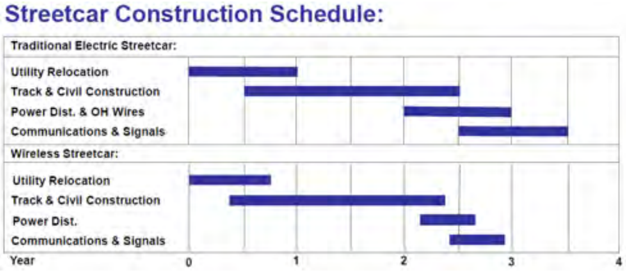
	Cost per Mile
Poles & wires	2,500,000
Special hardware	250,000
Substations	1,250,000
Utility power feeds	500,000
Duct banks	300,000
Special rail isolation	250,000
Cathodic protection	200,000
Utility relocation	500,000
Savings per mile:	**$5,750,000**

Bridge and Tunnel Costs: There are other savings in systems with bridges and tunnels. These savings can only be quantified on a project specific basis, but they are easy to identify. Bridge widths can be reduced by 3 to 4 feet simply by eliminating the poles and wires. And accommodations for the power distribution cables are eliminated. At nearly $500 per square foot, bridge costs may be reduced by nearly $2,000 per linear foot. A wireless system also means less overhead clearance, which could eliminate the need to raise existing overhead bridges and the need for additional bridge safety and maintenance considerations.

In twin bore (single track) tunnels, the tunnel diameter is generally determined by the combined height of the track, vehicle, and the overhead wire system. Eliminating the overhead wires, and the operating clearance for a raised pantograph, may allow for a smaller tunnel bore. Large bore (double track) tunnel diameters are generally dictated by the width of the track system, so tunnel bores for a wireless system may be nearly identical to a system with wires. But space in a tunnel is always at a premium and construction and maintenance in a tunnel is expensive, so eliminating the wires and power distribution cables may still result in significant savings. And locating substations in a tunnel is also expensive. They must either be housed in the passenger facilities or somewhere along the tunnel. Either way, the amount of cavern excavation required for their construction and maintenance is significant.

Construction Impacts: Wireless technology reduces construction impacts. It improves access to homes and reduces disruptions to businesses. The most disruptive elements of streetcar construction are the pole foundations, construction of the duct banks, and the relocation of utilities. All of these require excavation. The work is time consuming, noisy, and creates a considerable amount dirt and dust. It often requires detours, including pedestrian barriers, and sometimes the work is immediately in front of homes or commercial establishments. This work is greatly reduced with wireless technology, and the quality of life within the construction corridor is easier to maintain.

Urban construction



Construction durations are also reduced. In general, “stringing” the wire, powering the substations, and testing the electrical systems are among the last elements of work. This work requires specialized equipment and unencumbered access to the work site. Consequently, these tasks are only started when construction of the track and stations is nearly complete. Eliminating the electrical systems would reduce construction durations, and just as importantly, greatly simplify start up and commissioning of the Streetcar. A typical streetcar construction project that normally takes more than 3 years to complete could easily be reduced by more than 6 months. This also lowers costs by reducing the expenses related to overhead and financing.

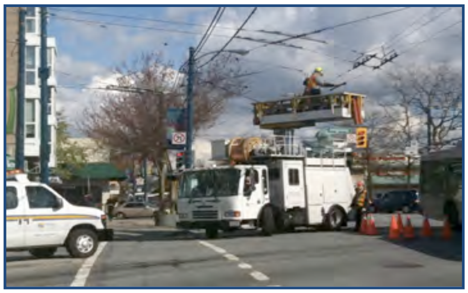
Vehicle Costs: The addition of battery equipment will result in added weight to the vehicle, resulting in added power costs. These costs, however, will be more than offset by using regenerative braking to directly recharge the batteries. Based on a fleet size of 7 cars, operating at an average of 20 hours per day and running 50,000 car miles per year, an annual savings of about $150,000 in power consumption could be realized.

eBrid Streetcar

The lithium-ion batteries and associated equipment used in Kinkisharyo’s e-Brid system have proven to be very reliable and require no regular maintenance. Current life expectancy is conservatively estimated to be about 8 years. But battery technology is improving daily and batteries with a 20 year life are expected in the near future. The current cost of battery sets is approximately $240,000. If we assume changing the batteries twice in 30 years, then the annualized maintenance costs would be about $55,000 for a fleet of 7 vehicles.

A new 5 mile wireless system would require two charging stations at $500,000 each and the initial cost per vehicle will be increased by about $350,000, resulting in an added capital cost of $3,450,000.

Operations & Maintenance: Wireless technology simplifies operations and maintenance, especially in climates with inclement weather. Winter storms play havoc with overhead wire systems. Ice accumulation can cause "arcing" which damages the pantographs, and can even go as far as to cause "snags" which rip the pantograph off the roof of the car or pull down the wire. It is not uncommon for operators to schedule non-revenue "ice runs" ahead of normal service just to clear the catenary system of dangerous accumulations of ice and snow. These non-revenue runs are costly, complicate service schedules, and are not an efficient use of the revenue fleet. In older "constant length" catenary systems another problem is loose wires in the summer and wire breaks in the winter as the system tries to expand and contract with the temperature change. Even in ideal climates, catenary systems are expensive to maintain. Both the wires and the substations require regular inspection and maintenance. Substations and power feeds also require a level of security, including protective fencing and intrusion alarms, which must be inspected, tested and maintained. Wireless systems also eliminate the need for overhead wire maintenance trucks…specialized non-revenue maintenance units that are expensive to buy and can only be used efficiently on large systems. They also eliminate the spare parts and material stores of wire and catenary hardware. Even vehicle maintenance is reduced, as smooth and safe operation is dependent on the regular inspection and maintenance of the pantograph system. Wire maintenance crews are eliminated; the traditional job of "power dispatcher" is eliminated; critical safety and proficiency training associated with overhead wires is eliminated; and substation maintenance is limited to the charging station, usually located in the shop and yard area. On a small streetcar system, these improvements and efficiencies will result in operating cost savings of approximately $600,000 per year.


Overhead wire maintenance

Operating Cost Savings:

Wire & substation maintenance	460,000
Material, parts & supplies	55,000
Special equipment & tools	15,000
Operating efficiencies	30,000
3rd party support	40,000
Annual savings:	**$600,000**

Safety: Passenger and worker safety are improved with a wireless system. In the event of a loss of power, the need for a "rescue" vehicle to ferry passengers to the nearest station is eliminated; this is especially important if power is lost to vehicles in a tunnel.

Worker safety is improved, especially in the shop and yard area where employees routinely work above the roof line of the vehicles. The vehicle maintenance shop is the most dangerous area on the system. Moving vehicles in and out of the shop can only be accomplished by powering the vehicle through overhead wires, using a "hot stick", or moving vehicles using winches or a motorized tow. Overhead wires in the shop expose employees working above the roof line to dangerous electrical

Exposed wires in shop

equipment. “Hot sticks” are even more dangerous, requiring employees to handle tools with exposed electrical contacts. Winches and tow motors are much safer, but highly inefficient. Wireless technology overcomes all of those problems safely and efficiently; improving safety for employees and reducing maintenance costs.

Wireless technology also improves safety for 3rd parties working along the line. Streetcar operators must routinely provide protective services for contractors working along the right of way. Protection is required to ensure the safety of 3rd party employees performing inspection or maintenance of bridges which cross above the wires, or to ensure the safe operation of cranes and other high mast construction equipment operating near the wires. Most of the time, this protection includes a review of the contractor’s operations and equipment before work is started, and an inspector at the site to ensure compliance with safety procedures. Occasionally, contractors must work very close to the overhead wires. On those occasions the wires must be de-energized and grounds applied to protect the workers. Wireless technology will not eliminate the need to protect all work above the tracks, but it will eliminate the specialized protective services for electrical safety.

Another consideration is emergency response along the transit corridor. Responding to fires along the right of way often requires the deployment of ladders and other rescue equipment in close proximity to the wires. This requires closely coordinated and diligently rehearsed emergency procedures to ensure the safety of the emergency crews. Emergency response may also require de-energizing the wires and applying grounds, which can delay response time and further threaten life and property. Wireless technology eliminates the coordination of emergency response related to the electrified systems, and eliminates the need for rescue vehicles in the event of a total loss of traction power.

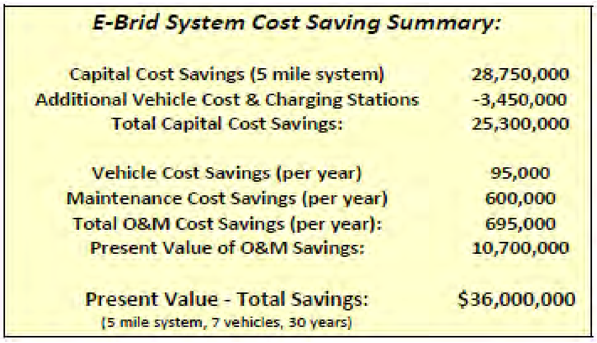
Yard Operations and Storage Tracks: The yard and shop area can also be designed more effectively, without regard to pole locations or power feeds. And track geometry can be developed independent of the complications of overhead wire geometry. Storage tracks can be closer together and save space. Yard and shop construction is easier and cheaper, and yard operations are more reliable. All of the storage is available all of the time, because shut downs for wire inspection and maintenance are eliminated.

Poles in storage yard

Summary: The advantages of a wireless system include significant savings in both the capital and operating cost, as well as potential savings associated with reduced rights of way, savings associated with civil works (especially bridges and tunnels), and with improved construction schedules. The disadvantages are limited to small increases in vehicle cost and battery maintenance.

Not accounting for the cost savings associated with right of way, shorter implementation schedules or civil works benefits associated with smaller bridges and smaller bore tunnels (which can only be evaluated on a project specific basis), the system-wide savings for a 5 mile wireless streetcar system could easily be as much as:

➢ Project Capital Cost Savings	**$25,300,000**
➢ Annual Operating Cost Savings	**$695,000**



E-Brid System Cost Saving Summary:	
Capital Cost Savings (5 mile system)	28,750,000
Additional Vehicle Cost & Charging Stations	-3,450,000
Total Capital Cost Savings:	25,300,000
Vehicle Cost Savings (per year)	95,000
Maintenance Cost Savings (per year)	600,000
Total O&M Cost Savings (per year):	695,000
Present Value of O&M Savings:	10,700,000
Present Value - Total Savings: (5 mile system, 7 vehicles, 30 years)	$36,000,000

For a 5 mile streetcar system utilizing a fleet of 7 e-Brid vehicles, the estimated annual operating cost savings could be capitalized (at 5%) as $10.7 Million, and when combined on a present worth basis the total cost savings could be about $36 Million over the 30 year life of the system.

The advantages of wireless streetcars will continue to expand. Existing battery technology limits a completely wireless system to about 5 miles. But battery storage systems will get smaller and lighter even as their capacity grows, and the range of wireless systems will be extended. Construction schedule savings together with capital and operating cost savings will make streetcar systems financially more attractive, and eliminating wires and substations will make them aesthetically and environmentally more acceptable. The improvements in electrical and passenger safety are priceless, especially when they come at no cost.

Even longer streetcar lines can benefit from wireless technology. Wireless streetcars can be especially useful in cities with historic districts that prohibit the introduction of wires. They can “bridge the gap” by running conventionally outside the historic district, then lower the pantograph and operate without wires within the district. They may also be able to lower the cost of systems with tunnels by lowering the cost of tunnel construction and maintenance.

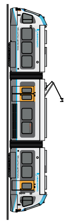
Wireless technology is no longer experimental. It is ready for commercial use now and will quickly become the preferred solution for shorter streetcar lines and downtown circulators in an urban environment. And wireless systems offer benefits that may provide value even for longer systems. Most importantly, they are faster and cheaper to build, easier and less expensive to maintain, and they result in a more aesthetically pleasing product.

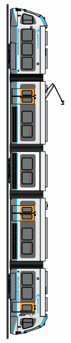
Note: The information in this report was based on typical project data and from manufacturer’s data provided by Kinkisharyo. Costs for a specific project may vary depending on specific project conditions.

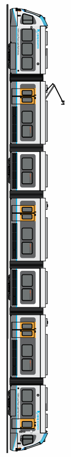
Vehicle Specification

ameri*TRAM*™

		300	500	700
	Empty Weight with e-Brid ™	**32 mt** (70.5 klbs)	**48 mt** (105.5 klbs)	**64 mt** (141 klbs)
	Passengers (4/m2)	**115** (28 seats)	**150** (62 seats)	**190** (96 seats)
Primary Dimensions	Length over Anticlimbers	**20m** (65 ft 7.4 in)	**30m** (98 ft 5 in)	**40m** (131ft 2.8 in)
	Width of Carbody *	**2.65m/2.46m** (8 ft 8.3 in/8 ft 1 in)		
	Width of Thresholds *	**2.71m/2.52m** (8 ft 10.7 in/8 ft 3.2 in)		
	Height of Carbody	**3.8m** (12 ft 5.6 in)		
	Boarding Height	**350mm** (13.75 in)		
	Ceiling Height	**2472mm** (8 ft. 1.3 in.)		
	Clear door opening Double Door: Single Door:	**1220mm** (4 ft.) **815mm** (2 ft. 8.1 in.)		
Trucks	Truck Centers	**10.8m** (35 ft. 5.2 in.)		
	Wheel Diameter	**600mm** (23.6 in.)		
	Wheel Base	**1800mm** (70.9 in.)		
Operating Parameters	Maximum Grade **	**9%**		
	Minimum Horizontal Curve	**18m** (60 ft.)		
	Minimum Vertical Curve (+/-)	**350mm** (1150 ft.)		
	OCS Voltage (DC)	**750 nominal** (525-900 range)		
Performance	Maximum Service Speed	**80 kph** (50 mph)		
	Acceleration **	**1.3m/s^2** (3.0 mphps)		
	Service Brake	**1.3m/s^2** (3.0 mphps)		
	Emergency Brake	**2.3m/s^2** (4.5 mphps)		
Primary Systems	Propulsion	**IGBT Inverter with VVVF Controls**		
	Friction Brake	**Hydraulic Disc**		
	Auxilary Power	**208vAC - 3phase - 60hz**		
	LVPS	**24vDC**		

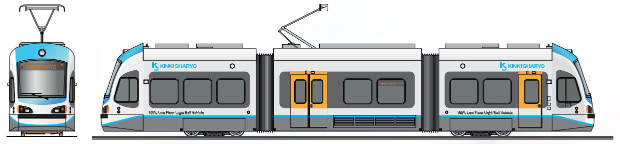




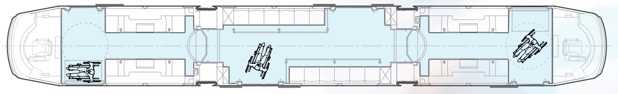


*Available in wide (LRV) or narrow (Streetcar) versions

**All axles powered


KINKI SHARYO
KINKI SHARYO
100% Low Floor Light Rail Vehicle
100% Low Floor Light Rail Vehicle

ameri*TRAM*™ Streetcar, exterior



ameri*TRAM*™ Streetcar, interior

KINKISHARYO International, LLC
US Headquarters:

400 Blue Hill Drive, Suite 3B
Westwood, MA 02090

T. 1-888-4-SHARYO (474-2796)
E. businessdevelopment@kinkisharyo.com

For more information please visit
www.kinkisharyo.com
www.ameritram.com

KINKISHARYO
Engineering Sustainable Urban Transit

ameri*TRAM*™

The 100% Low-Floor Streetcar Engineered for North America

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ameriTRAM™

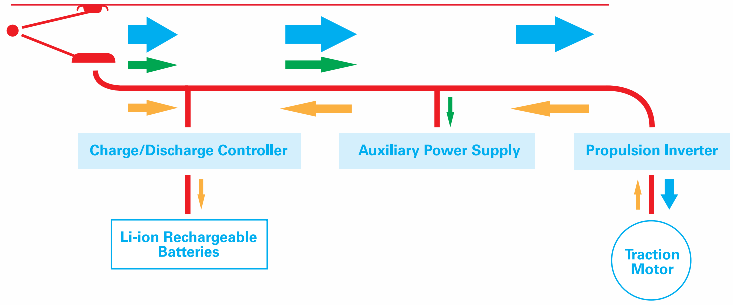
North America's 100% Low-Floor Streetcar

e-Brid™

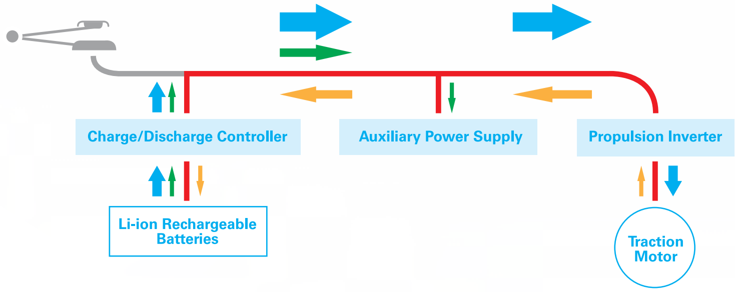
Electro-Hybrid Li-ion Battery Power Propulsion Technology

Through unique e-Brid ™ technology, *ameriTRAM* ™ is propelled by overhead catenary or on-board lithium-ion batteries. e-Brid ™ charges the batteries while running on catenary power; and, when in battery mode, uses electricity stored from regenerative braking.

Powered by Catenary



Powered by Li-ion Batteries



Through e-Brid™ technology *ameriTRAM*™ provides:

+ **Superior Versatility**
  Achieve propulsion where overhead contact wire cannot be installed

+ **Historic Preservation**
  Free downtown and historic areas of overhead wires

+ **Improved Aesthetics**
  Minimize environmental impact and improve visual aesthetics through wireless sections

+ **Reduced Energy Usage**
  Realize immediate savings though lower power consumption via "peak-shaving"

+ **Greater Value**
  Save millions in capital investment and operational costs with less electrification equipment and maintenance

+ **Enhanced Public Safety**
  Ensure safety of passengers in power outages or inclement weather

+ **Environmental Responsibility**
  Realize fewer greenhouse gas concerns through zero emissions and lower energy usage

Engineered For North America

ameriTRAM ™ is the only streetcar in North America that is compliant with ADA, Buy America, NFPA-130 and ASME RT-1

100% Low-Floor

With its 100% Low-Floor, *ameriTRAM* ™ offers:

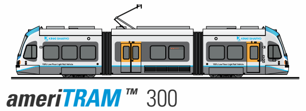
+ **Improved Passenger Safety**
  100% low-floor with no interior steps or ramps

+ **Superior Access**
  ameriTRAM ™ provides easier access and complies with all ADA requirements throughout the passenger area

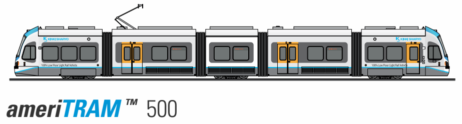
+ **Greater Efficiency**
  Faster boarding means less dwell time at stations

Flexible Modularity

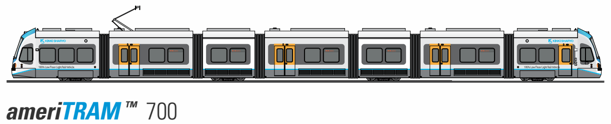
Expandable design allows for future system growth without increasing fleet size



ameriTRAM™ 300



ameriTRAM™ 500



ameriTRAM™ 700

KINKISHARYO International, L.L.C. is the #1 supplier of low-floor light rail vehicles in North America.

With the introduction of *ameriTRAM* ™, Kinkisharyo is the only light rail manufacturer to supply North America with a 100% low-floor, electro-hybrid, zero-emission streetcar powered by either overhead electric catenary or on-board lithium-ion batteries. Headquartered in Westwood, MA, KINKISHARYO has been redefining urban light rail transit systems throughout the U.S. for nearly three decades.

For more information on *ameriTRAM*™
www.ameritram.com

KINKISHARYO International, L.L.C.
400 Blue Hill Drive, Suite 3B
WESTWOOD, MA 02090
TELEPHONE: (781) 320-1220 FACSIMILE: (781) 320-1201

April 5, 2013

Mr. Jose R. Bustamante, PE
Director of Transit & Rail
RK&K
81 Mosher Street
Baltimore, MD 21217

Subject: Union Station – Georgetown Alternatives Analysis

Dear Mr. Bustamante:

Thank you for the opportunity to contribute to the study your firm is performing for the Georgetown Waterfront to Union Station Alternatives Analysis. Set out below are responses to the Supplier Questionnaire regarding streetcar vehicle and alternative propulsion technologies.

Question #1

The District will consider designs which allow for the use of an in-street conductor which supplies power to the vehicle continuously while operating, a system with long gaps in the overhead supply and wired areas for recharging while operating (batteries), or a system which charges an on-board storage system only when stopped at station platforms (supercapacitors or flywheels). Which of these types of systems have you supplied vehicles (rail, bus, or other transport) for? Or, are in the process of supplying? Do you have any comments on the advantages or disadvantages concerning the three system types?

Response:

Kinkisharyo has developed a LiIon battery 100% Low Floor vehicle that has off wire capabilities. This vehicle was demonstrated in the US at Charlotte, Dallas, and Phoenix where dynamic performance was demonstrated. It was also displayed statically at several locations. This vehicle can be seen at www.ameritram.com

The ameriTRAM as presently configured can be charged via an Overhead Contact System through a pantograph. This gives it the flexibility to operate over existing non-proprietary infrastructure. The vehicle can also be configured for inductive charging at fixed locations or a combination of both.

Flywheels are unproven. Supercapacitors are limited by the energy density which limits the distance that can be traveled. In street conductors are proprietary and limit the source of supply, especially for future expansions.

Question #2

A traditional streetcar is designed to operate from an overhead supply system operating continuously at either 600 or 750 Vdc. Would your company's offering place any special or additional requirements concerning integration of the electrification system? Would your technology operate with a pantograph when not on a wireless section?

Response:

Yes. Our technology uses a pantograph for wired right of ways. We prefer 750 Vdc but can configure to operate at the lower voltage.

Question #3 - In Street Conductors

Has the in-street conductor been utilized in areas which normally experience snow and ice in the winter? What material would you use for fabricating in-street conductors? Would the material show corrosion for the application of de-icing road salt? What provisions are made to prevent snow plow blades from damaging the rail?

Response:

Kinksharyo studied this type of operation but chose to develop a system that would operate on non-proprietary OCS systems due to the requirements for heaters, drains (flooding) and road damage.

Question #4 – In Street Conductors

Has the in-street conductor been installed in mixed use traffic lanes? Has it been installed in reserved lanes with normal traffic operating at right angles across it? Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

Response:

Not applicable to Kinkisharyo ameriTRAM.

Question #5 – In Street Conductors

How is the conductor installed in the street? Are there any restrictions on horizontal or vertical curvature of the pavement? How are crossings or turnouts implemented with the conductor rail? What clearances are required for other structures such as manholes and metallic covers?

Response:

Not applicable to Kinkisharyo ameriTRAM.

Question #6 – Batteries

Which battery type do you have experience in applying, Lithium (Li) or Nickel Metal Hydride (NiMH)? What is the maximum acceleration rate and maximum speed normally used in these applications?

Response:

Kinkisharyo's ameriTRAM uses Lithium Ion Batteries. Kinkisharyo limits acceleration in battery operation mode to increase battery life. Acceleration in battery mode is limited to $0.9 m/s^2$ ***(2mphps). Speed is limited to 40 mph. Acceleration in wired mode is*** $1.34\ m/s^2$ ***(3mphps).***

Question #7 – Batteries

What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third-party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

Response:

The limit of charge/discharge is defined by our battery supplier dependent upon the battery chosen for this application. The charge / discharge capabilities are very high approaching 600 amperes. See link below for battery data sheet. The battery management system is provided by the battery supplier. Individual cells are monitored.
http://www.gsyuasa-lp.com/LIM30-lithium-battery

Question #8 – Batteries

The operating environment in DC has a temperature range of -15^{0} F to 106^{0} F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

Response:

These temperatures do not cause a concern for the Kinkisharyo battery system. The cells are cooled via fans that are part of the battery trays.

Question #9 – Batteries

There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

Response:

In the ameriTRAM the batteries are mounted low on the side of the vehicle and protected by side frame bars that act to reduce damage if a traffic mishap occurs. The battery mounting location is no more vulnerable than a side door entry.
If batteries are damaged in any way they should be removed from the vehicle and discharged.

The batteries have been qualified to the UN testing criteria for the transport of dangerous goods. UN 38.3 includes Tests 1-8 of this specification:
T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)
T2 – Thermal Test (Primary and Secondary Cells and Batteries)
T3 – Vibration (Primary and Secondary Cells and Batteries)
T4 – Shock (Primary and Secondary Cells and Batteries)
T5 – External Short Circuit (Primary and Secondary Cells and Batteries)
T6 – Impact (Primary and Secondary Cells)
T7 – Overcharge (Secondary

Question #10 – Batteries

Batteries will be discharged during overhead gaps and recharged while operating in wired sections. As a “ball-park” approximation, if a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge? What would be the maximum current draw for battery recharging?

Response:

In order to accurately determine the battery performance a simulation of the route profile would have to be performed. This profile would include regeneration charging in braking and loading from acceleration, grades, and auxiliaries. The simulation would take into account a discharge of the batteries at the start of the

simulation to approximately 90% of battery charge and discharge down to about 40% SOC. After performing the simulations Kinkisharyo would work with the wayside designer to optimize placement of charging wire sections. This iterative design approach is the best way to optimize the systems design.

The battery charging current while stopped is limited to 200 amps. The charging current while braking is higher to optimize regeneration energy recovery. For a 50% discharge as described above it takes approximately 16 minutes to recharge back to the 90% level.

Question #11 – Batteries

If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106^0 F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160^0 F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

Response:

Charging currents are limited. KI uses a 4 carbon pantograph to spread the charging current density. Additionally, for areas where the vehicle will be stopped for a long time on a consistent basis charging bars can be added to the overhead to spread demand and reduce charging density. The stationary current for charging with full auxiliary loads will be approximately 300 amps.

Question #12 – Supercapacitors

What is the time required to recharge fully depleted supercapitors at a stop? What level of current and voltage is this time based on?

Response:

Not applicable to Kinkisharyo ameriTRAM.

Question #13 – Supercapacitors

For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

Response:

Not applicable to Kinkisharyo ameriTRAM.

Question #14 – Supercapacitors

If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

Response:

Not applicable to Kinkisharyo ameriTRAM.

Question #15 – Batteries & Supercapacitors

Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Response:

Kinkisharyo's ameriTRAM can be configured to load shed and have performance limits imposed based on the battery state of charge. We recommend traffic light preemption to limit stopping.

A rescue vehicle could be developed that would be used for recharging the vehicle in the street or could power the vehicle until it reaches a wired segment.

Question #16 – Vehicle Design Criteria

The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

Response:

These are Czech widths. European widths are different. Refer to the street car guidelines being prepared by APTA for standard widths. Kinkisharyo recommends the 2650mm width to increase passenger loading and provide interoperability with LRV systems, but can build to the narrow width if the quantities of vehicles are significant.

Question #17 – Vehicle Design Criteria

The District's current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

Response:

The Kinkisharyo ameriTRAM vehicle is 20m over the anticlimbers and accommodates the energy storage equipment.

Question #18 – Retrofit of Existing Vehicles

The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

Response:

Kinkisharyo recommends that these vehicles be sold to authorities that are operating similar vehicles with similar widths. Portland, Seattle, Tacoma, and possibly Tucson would be candidates. These vehicles should be replaced as part of the procurement to keep the fleet and its maintenance practices/ parts common and to have state of the art wireless operation.

Question #19 – Specialized Equipment

What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

Response:

The Kinkisharyo ameriTRAM does not require specialized equipment over that found in modern vehicle maintenance facilities. High voltages exist on any streetcar. Testing and troubleshooting practices will have to take into account procedures to deal with LiIon batteries and high voltage in the form of batteries.

Question #20 – Training and Education

Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?

Response:

The Kinkisharyo ameriTRAM is designed to be maintained by personnel who maintain electrically power railcars. No advanced training is required other than maintainer / operator training for the battery systems which would be included for a vehicle of this type. The vehicle has the batteries, battery monitor system, and the charge discharge controller that are in addition to typical electrical equipment found on electrically powered railcars.

Also included with this letter are the following materials:

- Kinkisharyo International brochure
- ameriTRAM brochure
- Wireless Streetcar Savings

I will contact you early next week to discuss arrangements for a technical interview including the possibility of a telephone conference call. If this is feasible, we can furnish a call-in number for the call.

Sincerely,

WJKleppinger

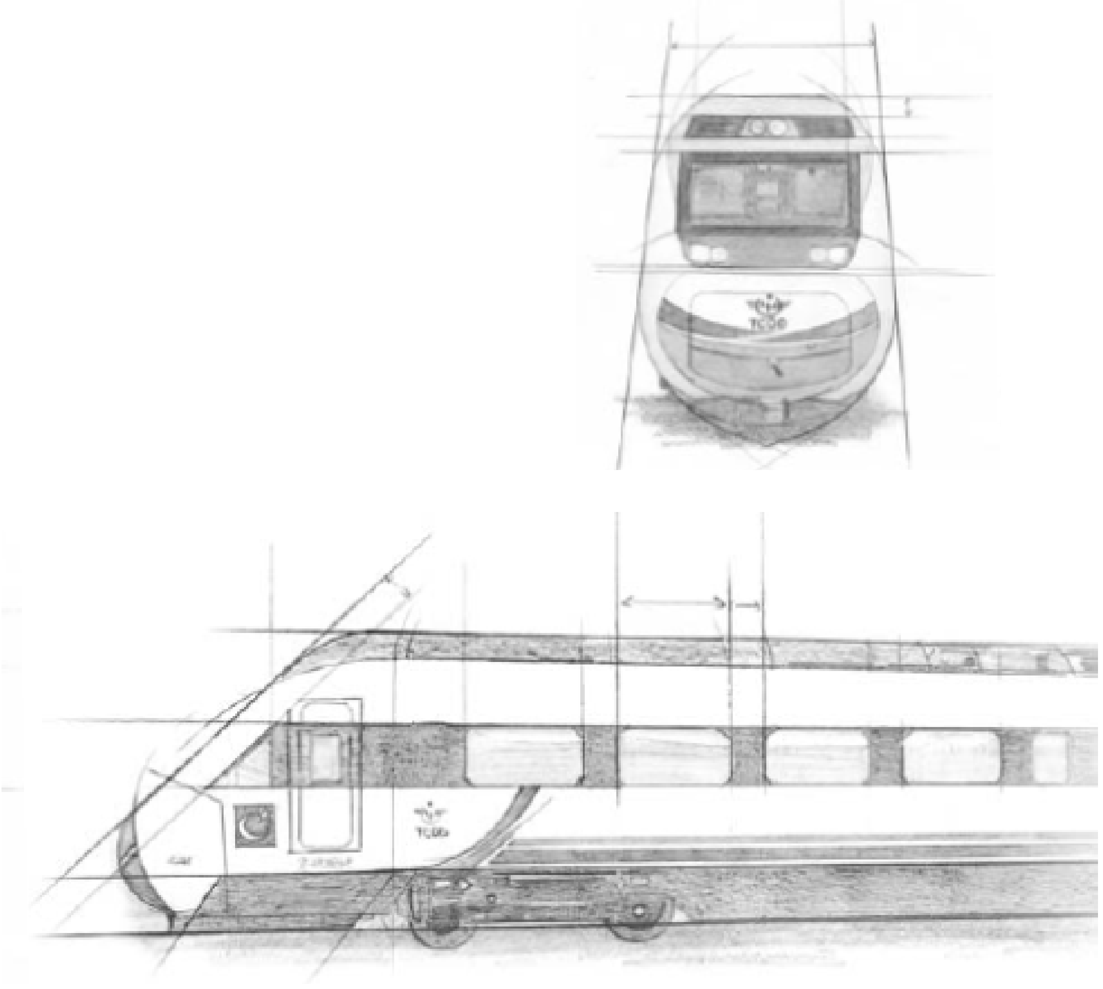
W. J. Kleppinger
Business Development / Program Management
KINKISHARYO International, LLC

CAF

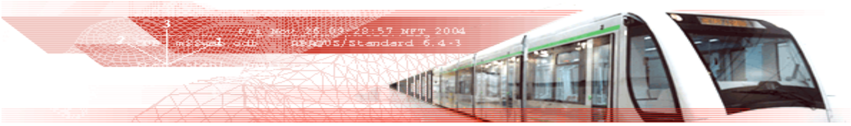
CONSTRUCCIONES Y AUXILIAR DE FERROCARRILES, S.A.

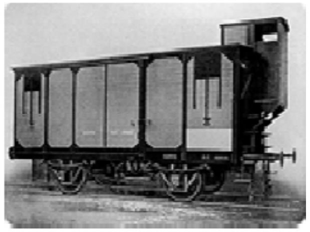
Presentation Index

- History
- Products and services
- Production facilities
- CAF Group
- International presence
- CAF in figures



History





1860–1906: Industrial workshops for the repair and assembly of wagons

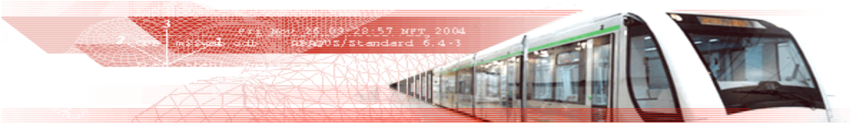
1897: Zaragoza: Establishment of "Carde y Escoriaza" First tram manufactured in Zaragoza.

1917: Establishment of the company "Compañía Auxiliar de Ferrocarriles, S.A." with headquarters in Beasain Main activity: manufacture of freight wagons.

1969: Creation of the R&D unit strengthening technological development

1992-2000: International consolidation of the company

History

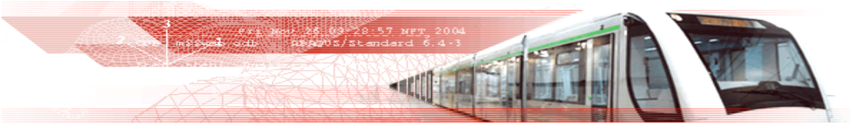


2006: Commissioning of the variable gauge BRAVA system for High-Speed Rail

2008: Start of the commercial Operation of suburban Train in Mexico, 30 year concession contract. DBOT Project

2010: Oaris, very high-speed train (350 km/h)

Products and Services

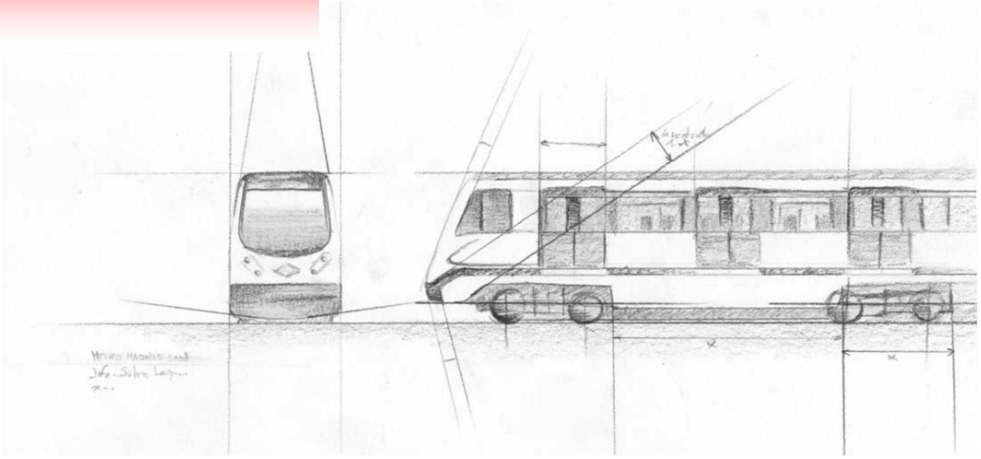


ROLLING STOCK

- Design and manufacture of all types of rolling stock

TURNKEY PROJECTS

- Turnkey
- Concessions



FINANCING

- Project financing
- Leasing/Renting
- Made to measure solutions

SUBSYSTEMS

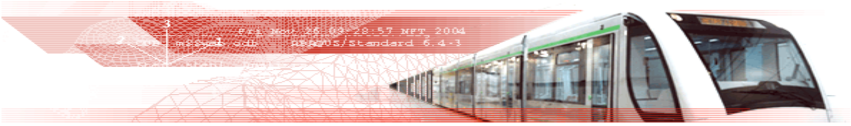
- Component Manufacture (wheels, axles, couplings, etc.)
- Equipment Supply (Trucks, Cosmos, Traction…)

ENGINEERING SERVICES

- Integration of Systems
- R&D
- Reliability Study
- Simulators
- Documentation
- Testing

AFTER-SALES SERVICES

- Maintenance
- Spare Parts Supply
- Repair
- Maintenance depot construction and equipment



Rolling stock

Wide range of products

High-speed trains

Regional trains

Suburban trains

Coaches

Subways

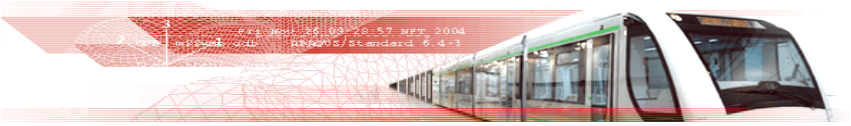
Airport shuttles

Trams

Articulated units

Locomotives

Facilities



➢ CAF BEASAIN

Total Surface Area:	446,000 m2
Staff:	2,432

Activities:
- Manufacture of Components
- Manufacture of Bogies
- Manufacture of Steel Car Bodies
- Manufacture of Aluminum Car Bodies
- Static testing of Car Bodies
- Painting
- Final Finishing and Testing

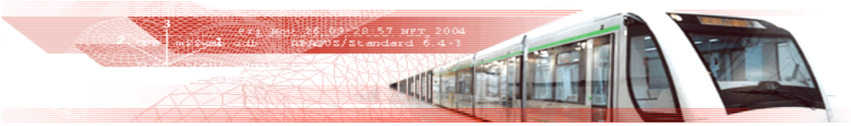
4. Facilities in Spain

- **CAF ZARAGOZA**

- **CAF IRUN**

- **CAF TRENASA - CASTEJON**

- **CAF SANTANA - LINARES**



4. Facilities outside Spain

CAF BRAZIL (HORTOLANDIA)

- Manufacture of steel car bodies
- Static testing of car bodies
- Painting
- Final Assembly and Testing

CAF FRANCE (CFD BAGNÈRES DE BIGORRE)

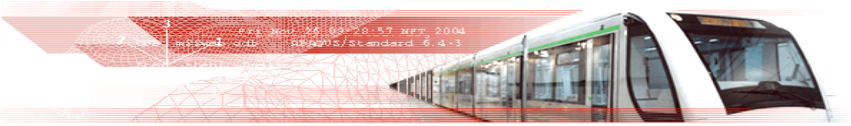
4. Facilities outside Spain

➢ CAF USA (ELMIRA)

- Static testing of car bodies
- Painting
- Final Assembly and Testing
- Manufacture of Car Bodies

➢ CAF MEXICO (HUEHUETOCA)

- Painting
- Final Assembly and Testing
- Manufacture of Car Bodies



CAF Group

CAF Group comprises more than 70 companies that work together to offer global railway solutions.

-**CAF Transport Engineering:** engineering and system electrification and integration.
-**CAF Signalling:** energy remote control and signaling
-**CETEST:** comprehensive testing and test management
-**Lander:** simulation systems
-**Danobat Rail:** depot equipment
-**CAF Power and Automation:** design and manufacture of electrical traction equipment for all types of trains, information and communication systems in the railway sector
-**Ennera:** renewable energy supply systems
-**Geminys:** integrated document management
-**NEM:** intelligent maintenance management systems.

CAF Power & Automation

CAF Signalling

CAF Transport Engineering

cetest CENTRO DE ENSAYOS Y ANÁLISIS

NEM solutions

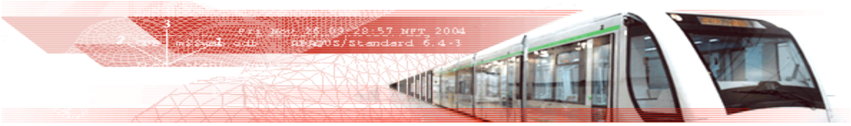
ennera energy for a new era

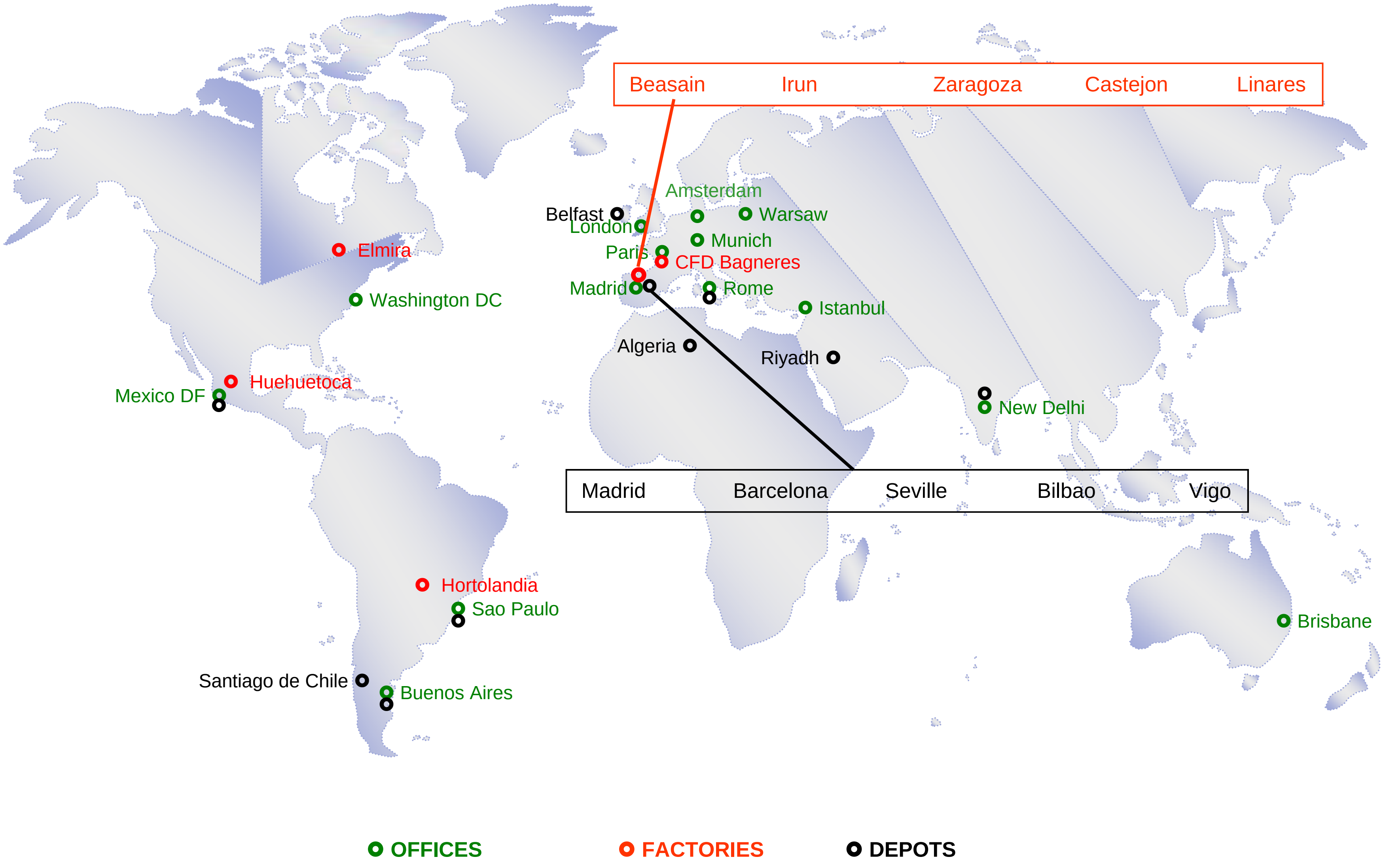
LANDER SIMULATION & TRAINING SOLUTIONS

Geminys gestión de manuales industriales e ingeniería

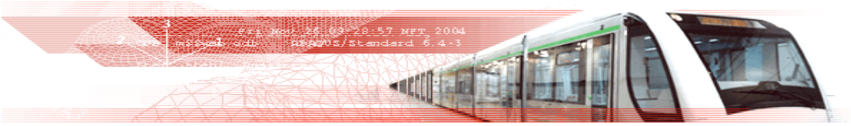
CAF

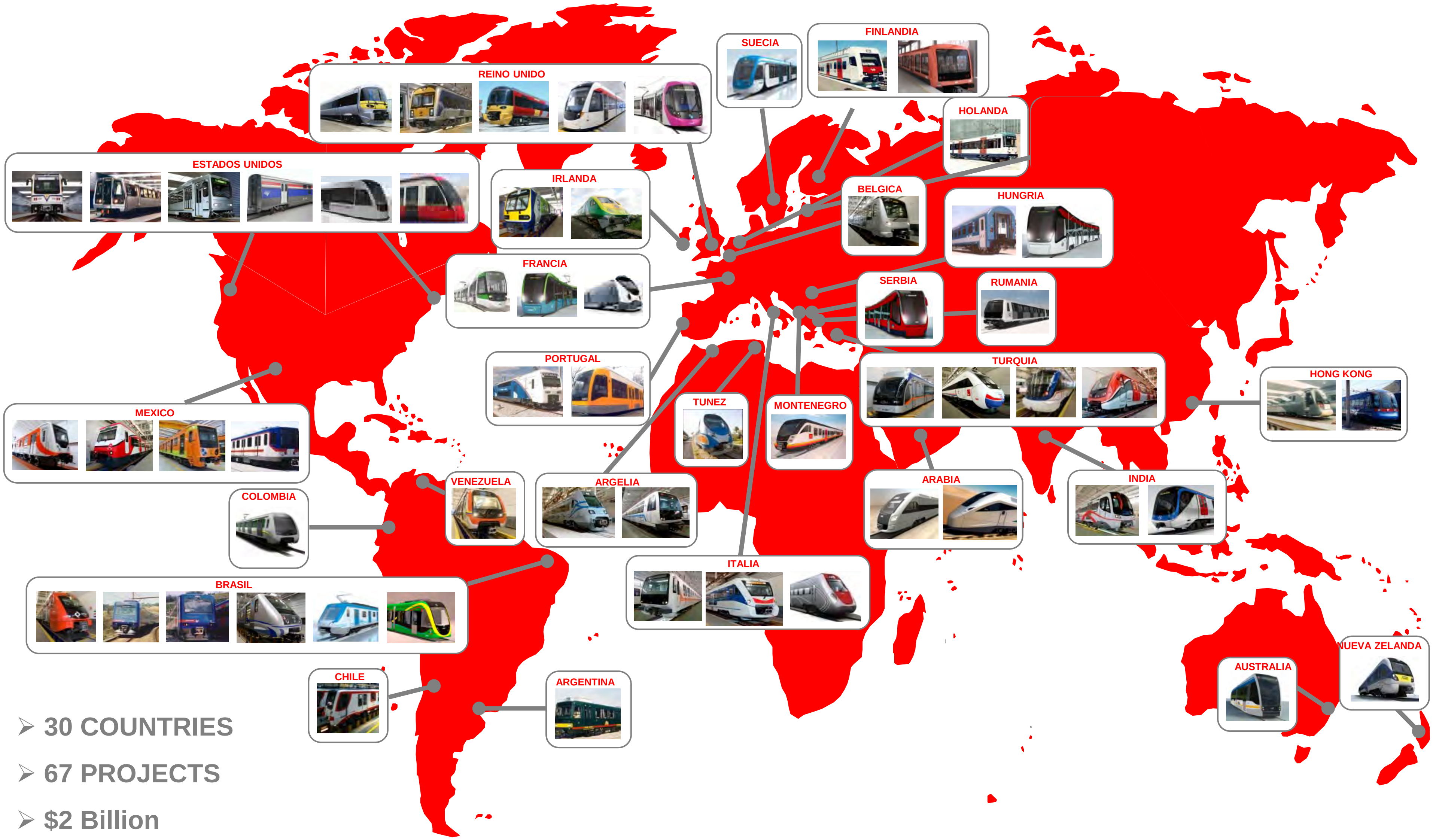
International Presence





International Operations



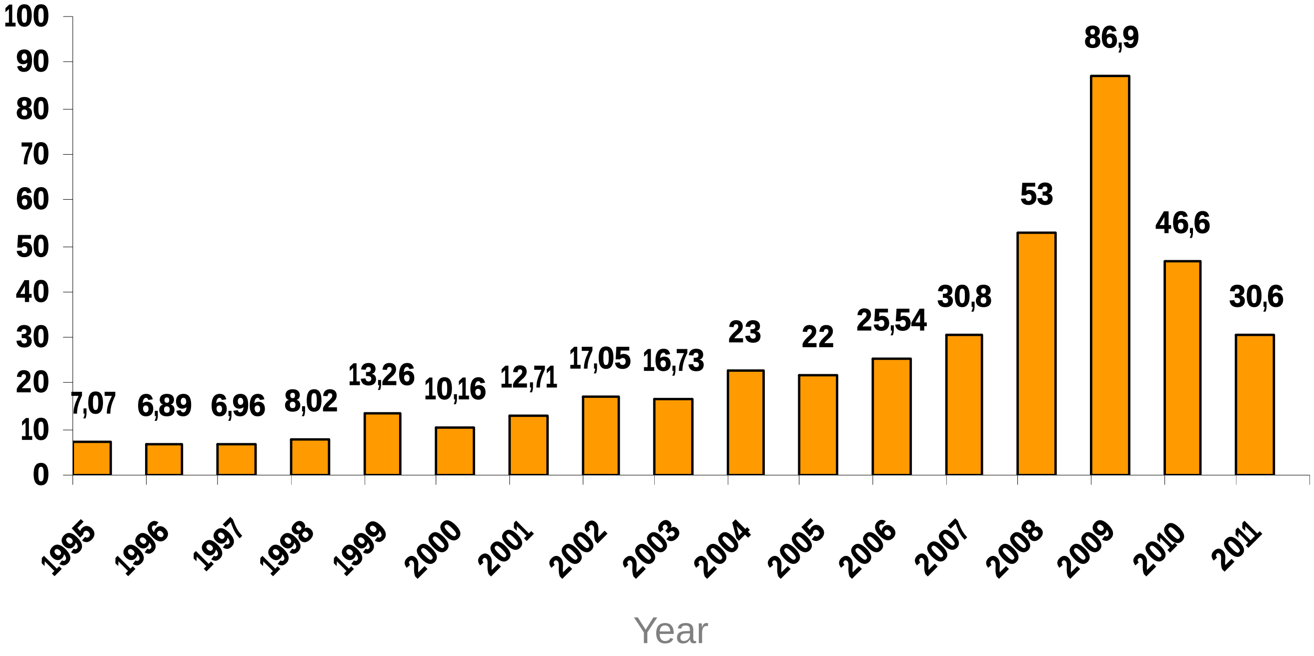


- ➢ 30 COUNTRIES
- ➢ 67 PROJECTS
- ➢ $2 Billion

Capital and Investments

- CAF is a private corporation with 100% of its shares listed on the stock market
- 29.56% employee participation
- 19.06% savings bank participation

INVESTMENTS



The investment figure since 1995 has reached more than 417 million €

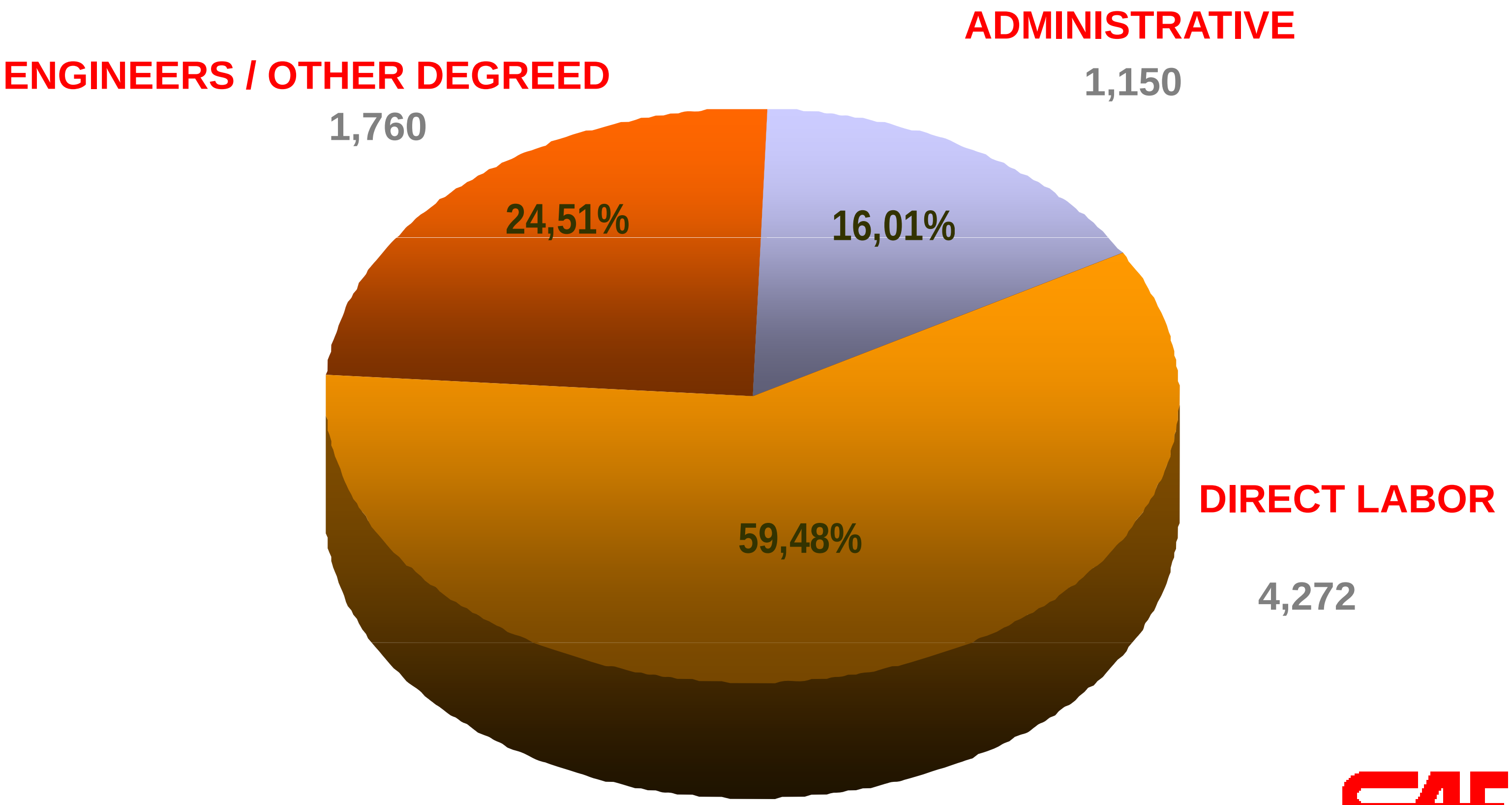
🟧 Million €

Workforce

30/09/2012:

CAF Group's total no. of employees 7,182

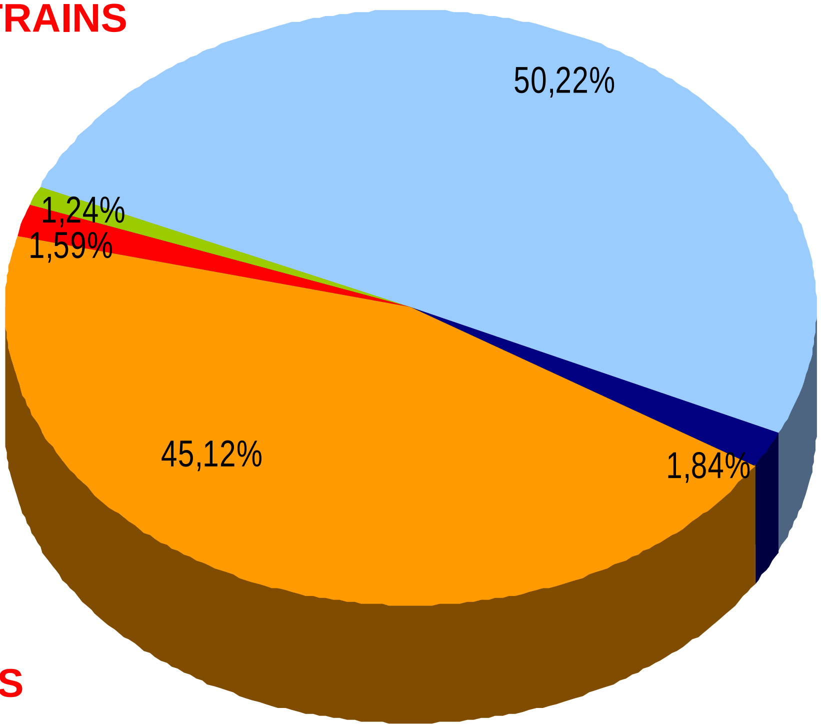
- CAF S.A.: 3,778
- Subsidiaries: 3,404



BACKLOG

30/09/2012:

Order portfolio: €4,859.09 Million



HIGH-SPEED TRAINS
60.11

SUBWAYS AND URBAN

2,440.16

LOCOMOTIVES

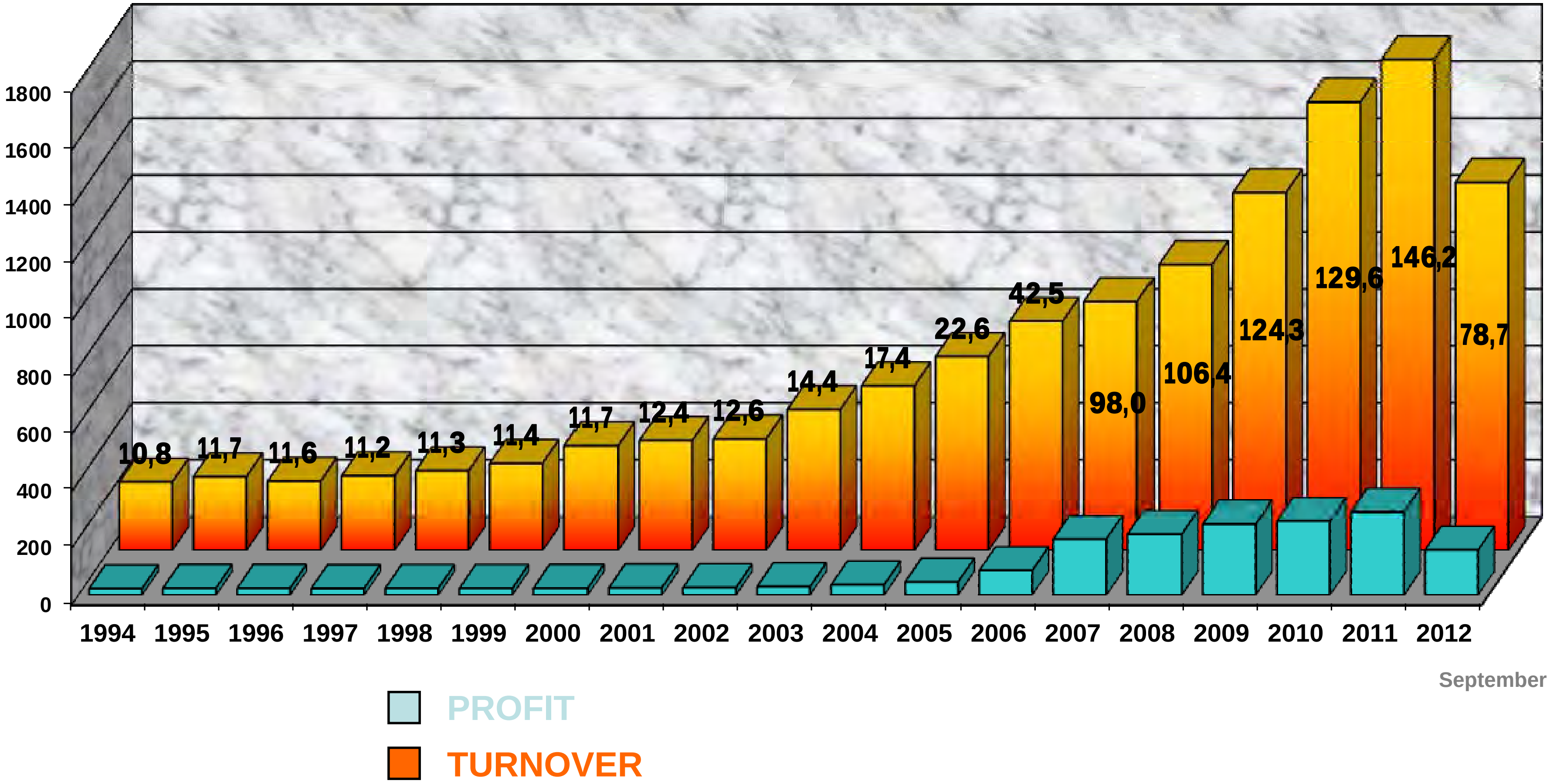
77.19

REPAIRS AND COMPONENTS
89.23

REGIONAL AND SUBURBAN TRAINS
2,192.39

Turnover and Profit

On the 30/09/2012, CAF is in a good position with respect to turnover and profit.



September 2012

We create railway solutions

March 22, 2013

CAF URBOS PLATFORM

Urbos 100% Platform

- Modularity and flexibility:
  - Uni-directional ⇔ Bi-directional
  - Multiple Configurations
  - Dimensions: length and width
  - Different Voltages: 650 Vdc, 750 Vdc and 1,500 Vdc
- Accessibility:
  - 100% Low Floor
  - ADA Compliant
- Optional Energy Storage System (Supercapacitors - ACR):
  - Energy Saving
  - Catenary-less Service
- Ease of Repair and Mantainability → Modular Construction

URBOS PLATFORM

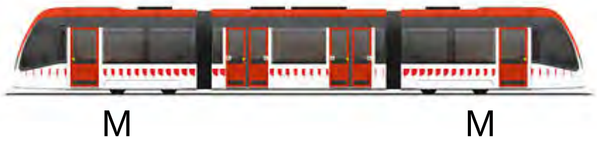
Urbos 100% Platform

- 100% Low Floor
- Different Configurations: 3, 5, 7 and 9 modules

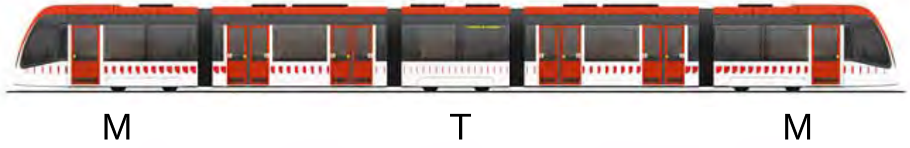
M- Motor Truck Module

T- Trailer Truck Module

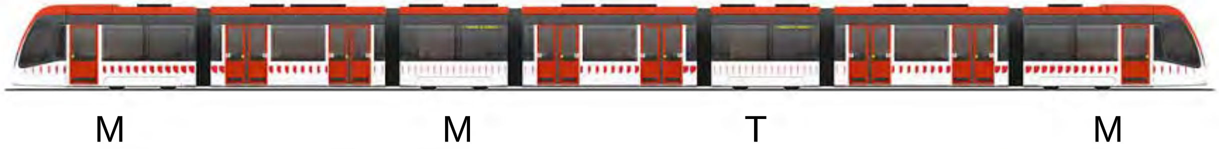
3 Module



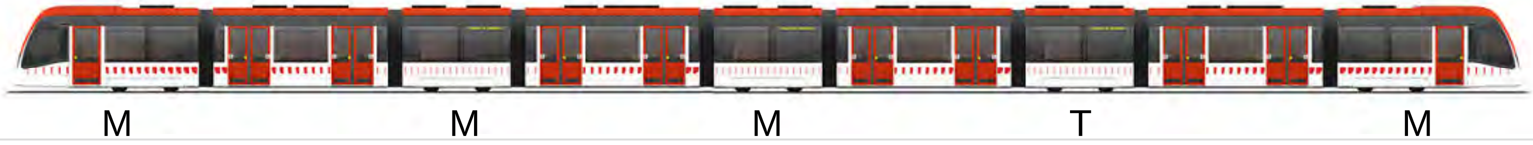
5 Module



7 Module



9 Module



URBOS PLATFORM

Track and Wayside Parameters

Supply Voltages:	650 Vdc, 750 Vdc and 1,500 Vdc
Track Gauge:	1,000 mm ⇔ 1,435 mm
Floor Height (TOR)	14”
Floor Height in Access (TOR to Threshold)	12-14”
Minimum Horizontal Curve Radius:	15 m for 1,000 mm gauge ⇔ 18 m for 1,435 mm gauge
Minimum Vertical Curvature:	1,150 ft
Maximum Gradient:	8-10% (3M-5M)
Minimum and Maximum Operating Heights:	
(w/o Supercapacitors – ACR)	11.48 – 22.22 ft
(w/ Supercapacitors – ACR)	12.38 – 22.22 ft

CAF

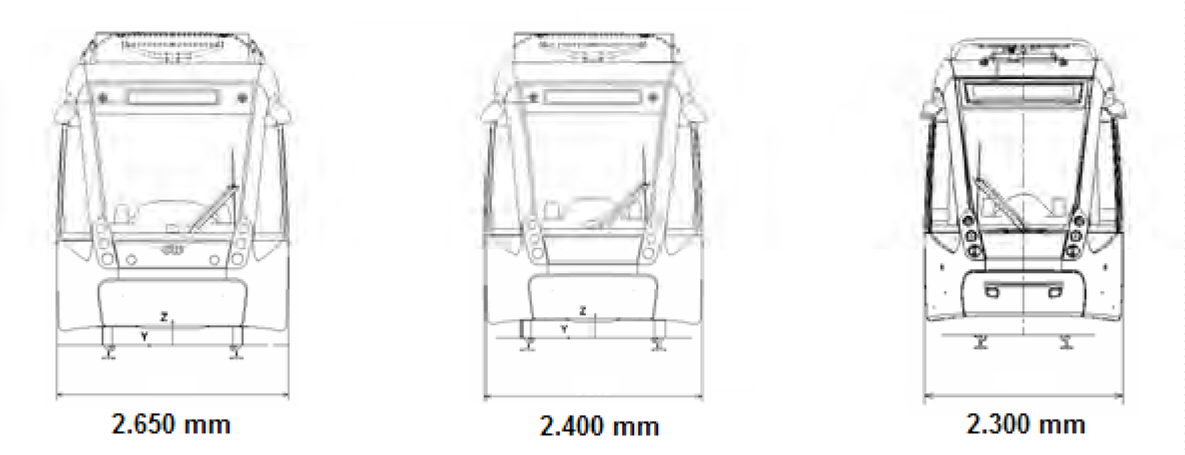
Technical Characteristics. Dimensions

- Standard Car Length:

3 Modules	69.29 ft to 77.50 ft
5 Modules*	106.19 ft to 124.56 ft
7 Modules	143.08 ft
9 Modules	179.97 ft

*Flexible Length of the Vehicle

- Carbody Width



Zaragoza Tram ➡ Sevilla Tram ➡ Belgrado Tram

Technical Characteristics. Doorway Dimensions

☐ Floor Height (TOR)	14”
☐ Floor Height in Access (TOR to Threshold)	12-14”
☐ Single door opening width:	32”
☐ Double door opening width:	51.2”
☐ Door Configuration per side:	
■ 3 Modules	2 double leaf + 2 single
■ 5 Modules	4 double leaf + 2 single
■ 7 Modules	6 double leaf + 2 single
■ 9 Modules	8 double leaf + single

Technical Characteristics. Capacities and Weights

- ☐ Capacity (2,650 mm width vehicles)

LRV Configuration	Seats	Passengers (4p/m2)	Total capacity
3 Modules	24	124	148
5 Modules	48	180	228
7 Modules	68	249	317
9 Modules	80	317	397

- ☐ Tare Weights
  - 3M Vehicle 76,850 lbs
- ☐ Maximum Axle Load 132 kN

URBOS PLATFORM

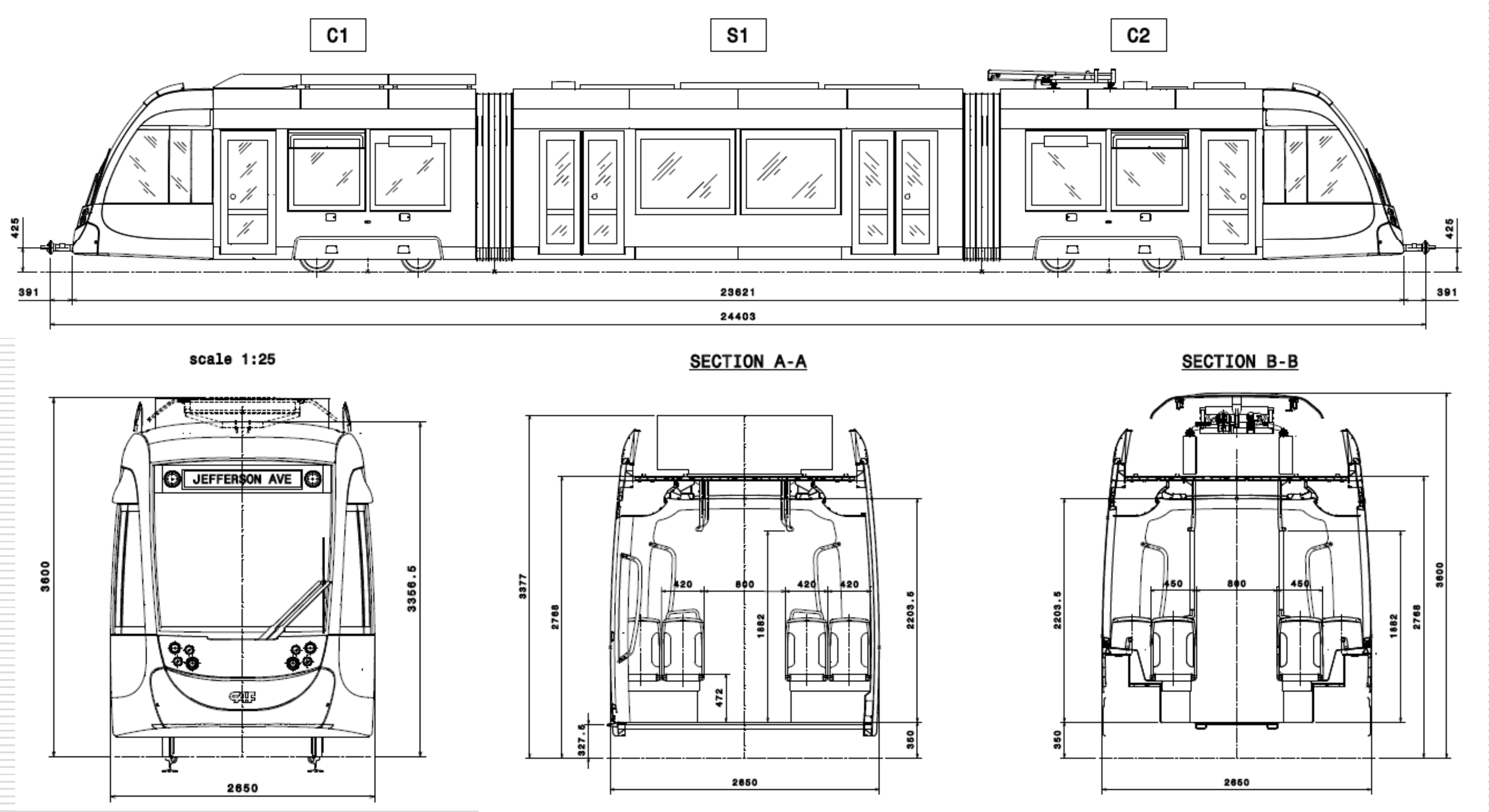
Technical Characteristics. **Vehicle Performance**

Supply Voltage	750 Vdc
Maximum Speed:	45mph
Nominal Power:	560kW (70kW per motor)
Acceleration:	3.0 mphps (1.34 m/s2) from AW0 to AW2
Deceleration rate (full service):	3.0 mphps (1.34 m/s2) from entry speed to zero
Deceleration rate (emergency):	5.0 mphps (2.23 m/s2) For 42 mph > entry speeds > 15 mph and it shall not exceed by more than 30%
Parking Brake	8%

Technical Characteristics. Base Configuration (3M USA)

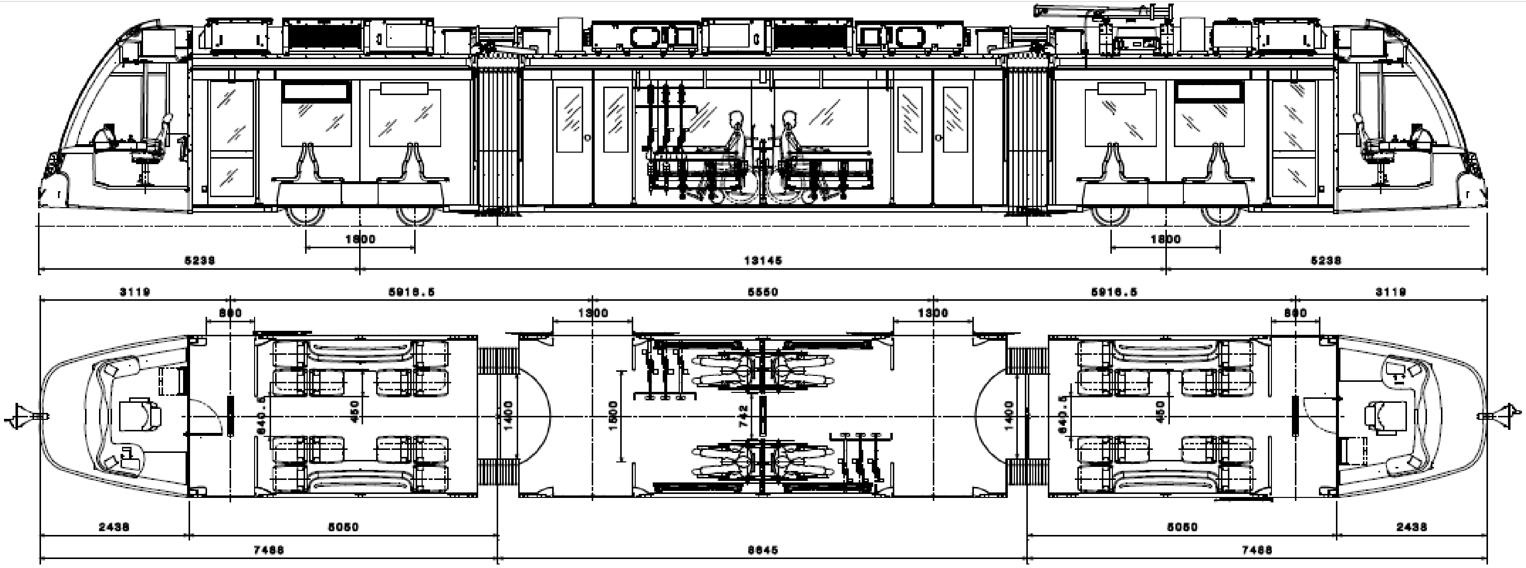
3 Modules:	C1-S1-C2
Body width:	8.69 ft
Unit height:	11.81 ft lowered panto
Floor height (TOR):	14”
Floor Height in Access (TOR to Threshold)	13.48”
Total length:	77.49 ft
Length between doors:	57.03 ft
Wheelbase:	70.87” motor truck
Bodybase:	43.12 ft
Wheel diameter:	23.22-20.07” (590-510 mm)
Vehicle capacity:	148 (24 seated -16%-, 148 @4p/m2)
Axle load:	132 kN EN 15663

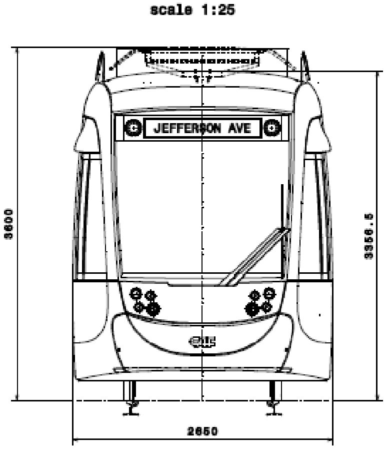
Technical Characteristics. Cincinnati (3M)



URBOS PLATFORM

Technical Characteristics. Interior Layout. Cincinnati (3M)

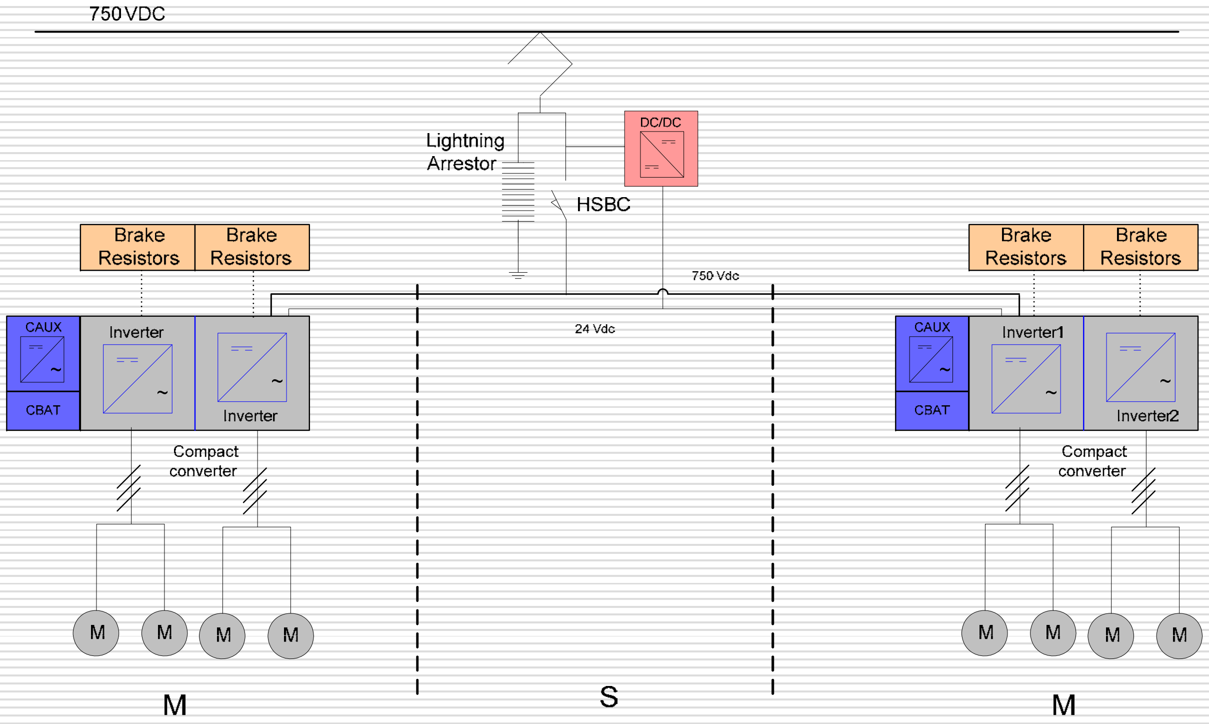




PASSENGER CAPACITY					
		C1	S1	C2	TOTAL
SEATED		12	(+12)	12	24 (+12)
AREA (m²)		5.64	20	5.64	31.28
STANDEED	4p/m²	22	80	22	124
	6p/m²	33	120	33	186
	8p/m²	45	160	45	250
TOTAL	4p/m²	34	80 (+12)	34	148 (+12)
	6p/m²	45	120 (+12)	45	210 (+12)
	8p/m²	57	160 (+12)	57	274 (+12)

Main Equipment. Traction and APS (3M)

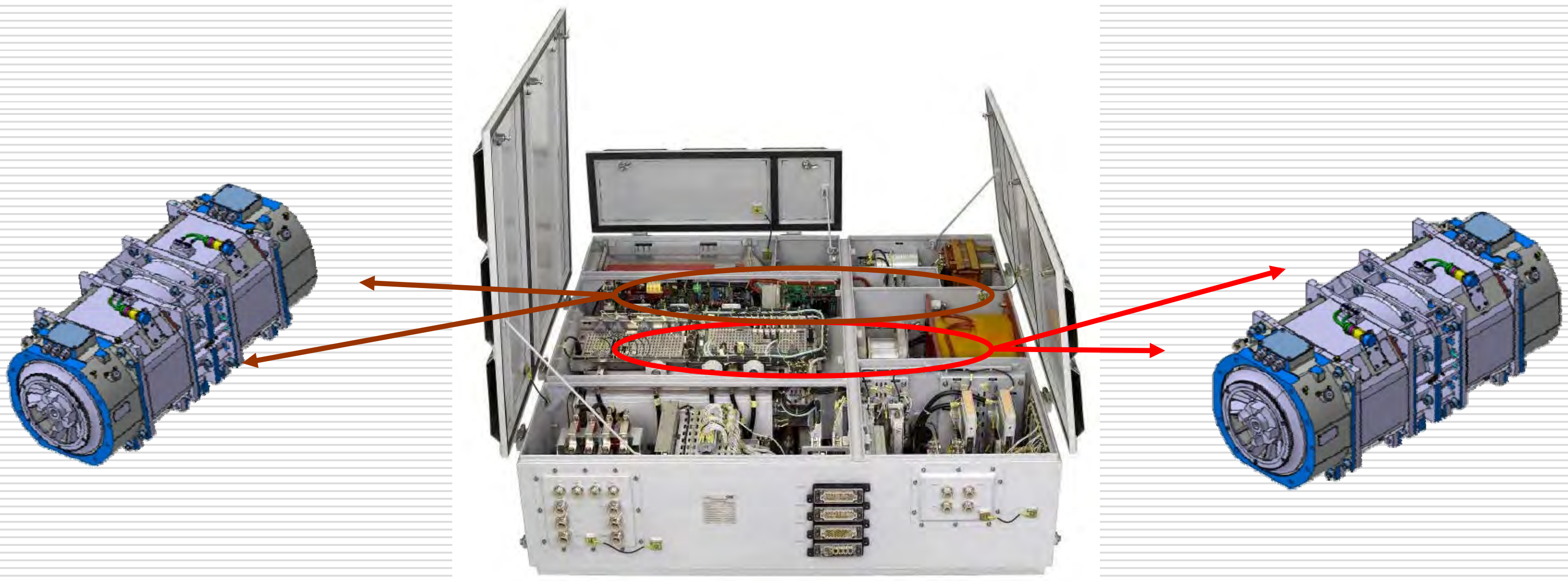
- ☐ Traction Inverter, Static Converter and Battery Charger consolidated in one Box
- ☐ Each Motor Truck has its own traction box, that consolidates 2 inverters



URBOS PLATFORM

Main Equipment. Traction and APS

- Each Traction Unit is controlled by the Electronics integrated in the Inverter Box.
- Each Inverter controls 2 Traction Motors of one side in order to reduce flange and rail wear and optimize curve negotiation.
    - Nominal Power: 61kW per motor.
- Self-Ventilated Motors
- Forced Air Cooled Inverters
- Regenerative and Rehostatic braking



Main Equipment. Traction and APS

The Auxiliary Power Supply consists of the following elements:

☐ 1 Auxiliary Converter (208 Vac, 60 Hz) integrated in each Traction Box of 50kVA

☐ 1 Battery Charger (28Vdc) integrated in each Traction Box of 5.5 kW

☐ 1 Battery (24Vdc) de NiCd de 110Ah per tramway

The Auxiliary Converters feed all the train loads redundantly.

In case of 1 Converter failure, the other Converters will feed the HVAC Units with a reduced performance and the rest of the loads of the vehicle.

On Board Energy Storage System

Why On Board Energy Storage System?

- ☐ Demand for increasingly cleaner and more efficient systems from an energy point of view.
- ☐ Growing concern about the visual impact of catenary in historical areas.

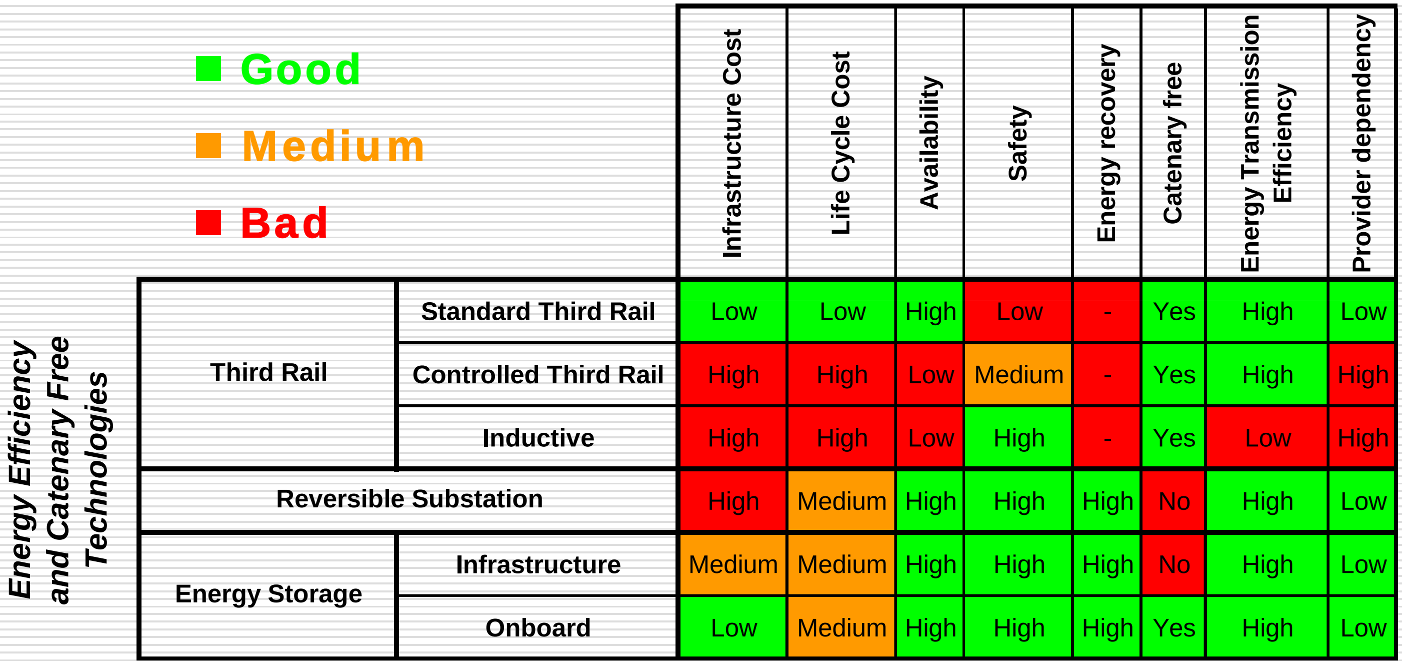
Alternatives

- ☐ Energy efficiency and solutions without catenary

🟩 **Good**

🟧 **Medium**

🟥 **Bad**



			Features							
			Infrastructure Cost	**Life Cycle Cost**	**Availability**	**Safety**	**Energy recovery**	**Catenary free**	**Energy Transmission Efficiency**	**Provider dependency**
Energy Efficiency and Catenary Free Technologies	**Third Rail**	**Standard Third Rail**	Low	Low	High	Low	-	Yes	High	Low
		Controlled Third Rail	High	High	Low	Medium	-	Yes	High	High
		Inductive	High	High	Low	High	-	Yes	Low	High
	Reversible Substation		High	Medium	High	High	High	No	High	Low
	Energy Storage	**Infrastructure**	Medium	Medium	High	High	High	No	High	Low
		Onboard	Low	Medium	High	High	High	Yes	High	Low

On-Board Storage Technologies

- After over 3 years of research to analyze, study, integrate and test different Energy Storage Solutions, such as:
  - Fuel Cells & Batteries (High Energy)
  - Flywheels, and Supercapacitors (High Power)

🟩 **Good**

🟧 **Medium**

🟥 **Bad**

Features

	Life Cycle Cost	**Energy density**	**Power**	**Fast charging**	**Availability**	**Safety**	**Maturity**
Fuel-cell (Hydrogen)	🟩 Low	🟩 High	🟧 Medium	🟩 Yes	🟧 Medium	🟥 Low	🟥 Low
Batteries	🟧 Medium	🟩 High	🟥 Low	🟥 No	🟩 High	🟩 High	🟩 High
Flywheel	🟧 Medium	🟥 Low	🟩 High	🟩 Yes	🟧 Medium	🟧 Medium	🟩 High
Supercapacitors	🟧 Medium	🟧 Medium	🟩 High	🟩 Yes	🟩 High	🟩 High	🟩 High

Batteries vs Supercapacitors

🟩 **Good**

🟧 **Medium**

🟥 **Bad**

	Energy density	Power	Life expectancy (approx. number of cycles)
Batteries	High	Low	2.000
Supercapacitors	Medium	High	1.000.000

Energy density

- Directly related to running range
- Battery energy quality ≠ Supercapacitor

Power

- Supercapacitors: Allows charging at very high current. Ultra-rapid charging process: 20 sec
- Battery: Longer charging period.

Life Expectancy (No. of Cycles)

- Supercapacitors: 1,000,000 Cycles
- Battery: 2,000 Cycles

TRAINELEC: GREENTECH PRODUCTS

greentech by trainelec

Trainelec's green product line

ACR evoDRIVE

Focused on **energy saving**, based on: **Supercapacitors**

ACR freeDRIVE

Focused on **catenary-free operating mode**, based on an Hybrid Technology: **Supercapacitors and Batteries**

URBOS PLATFORM

ACR evo DRIVE

- ☐ **Main Characteristics**
  - Energy supply optimization
  - Approximate energy saving 20%
  - Allows vehicles to run in catenary-free areas
    - ☐ Up to 100 meters of catenary-free area

- ☐ **EQUIPMENT**
  - DC/DC Converter
    - ☐ Supercapacitor charging and discharging Control
  - Modular Construction
    - ☐ 1 Supercapacitors Module

ACR evoDRIVE

Estimated Saving

- Equipment Conditions
  - 2 UC modules: 1.5 kWh/box
  - 1 Box for one 32 m LRV: 1.5 kWh/LRV

ACR Saving:		**18 - 23% of the energy**
ACR weight factor:	—	**1% more energy**
Net saving:		**17% - 22% Saving**

URBOS PLATFORM

ACR freeDRIVE

☐ Main Characteristics

- Allows vehicles to operate in catenary-free mode
- Improves Urban Landscape
- Reduces Infrastructure Cost
- Up to 1,400 meters catenary-free operating mode
- Approximate energy saving 25%

☐ EQUIPMENT

- DC/DC Converter
  - ☐ Supercapacitor/Battery charging and discharging Control
- Modular Construction
  - ☐ 4 Supercapacitors Modules
  - ☐ 1 Battery Module

GRUPO CAF

URBOS PLATFORM

ACR freeDRIVE

Estimated Saving

- ☐ Equipment Conditions
  - 4 UC modules and 1 battery module per box: 18.1 kWh/box
  - 2 Boxes for one 32 m LRV: 36.2 kWh/LRV

ACR Saving:		**27% - 32% of the energy**
ACR weight factor:	—	**5% more energy**
Net saving:		**22% - 27% Saving**

GRUPO CAF

URBOS PLATFORM

Videos

URBOS Projects

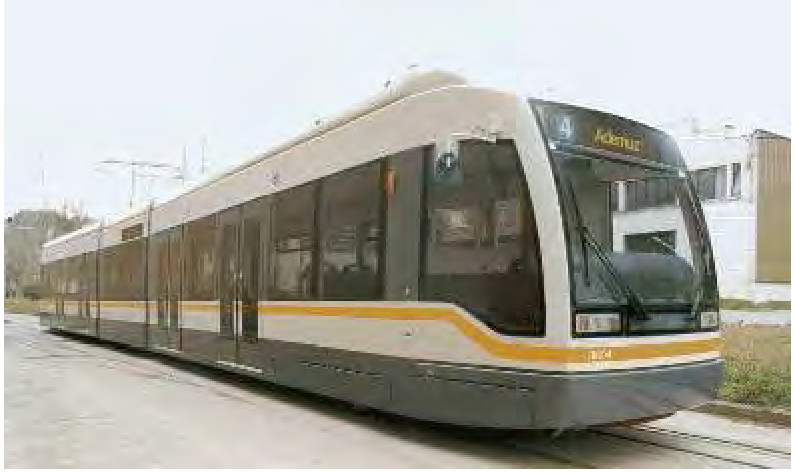
LRVs & Streetcars

Photo	Project	Customer	Country	No. Of Cars	Structure	Deliveries
	Valencia Tram – 70% Low Floor	FGV	SPAIN	12x3 = 36 4x3 = 12	Mc-T-M	1993-1994 1999
	Lisbon Tram - 70% Low Floor	CARRIS	PORTUGAL	6x3 = 18	Mc-T-M	1995
	Bilbao Tram - 70% y 100% Low Floor	Euskotren	SPAIN	7x3 (70%LF) + 1x3(100%LF) = 27	Mc-T-Mc	2002-2004
	Tram Vélez-Málaga - 100% Low Floor	LRV Vélez Málaga	SPAIN	3x5 = 15	Mc-T-T-T-Mc	2006
	Metro Centro Sevilla	TUSSAM	SPAIN	4X5=20	Mc-S-T-S-Mc	2007
	LRV Sevilla – 100% Low Floor	LRV Sevilla	SPAIN	17x5 = 85 5x5=25	Mc-M-T-M-Mc	2008
	Vitoria Tram 100% Low Floor	Euskotren	SPAIN	11x5 = 55	Mc-T-T-T-Mc	208-2009
	Antalya Tram	Antalya Metropolitan Municipality	TURKEY	14x5 = 70	Mc-S-T-S-MC	208-2009
	Edinburgh Tram	Tie Ltd	UK	27x7 = 189	Mc-S-T-S-M-S-Mc	2010-2011
	Zaragoza Tram	SEM	SPAIN	21x5 = 105	Mc-T-T-T-MC	2012-2013

LRVs & Streetcars

Photo	Project	Customer	Country	No. Of Cars	Structure	Deliveries
	LRV Malaga 100% Low Floor	Metro de Málaga	SPAIN	14x5 = 70	Mc-S-T-S-MC	2011-2012
	Belgrado Tram	GSP	SERBIA	30x5 = 150	Mc-S-T-S-Mc	2011-2012
	Metro Centro Sevilla - Extension	MetroCentro	SPAIN	4x5 = 20	Mc-S-T-S-Mc	2012
	Granada Tram	Ferrocarriles de la Junta de Andalucía	SPAIN	13x5 = 65	MC-S-T-S-MC	2012
	Nantes	Nantes Metropole	FRANCE	8x5 = 40	Mc S T S Mc	2012
	Besançon Tram	Communauté d'agglomération du grand Besançon	FRANCE	19x3 = 57	Mc-S-Mc	2013-2014
	Stockholm Tram	Storstockholm Lokaltrafik AB (SL AB)	SWEDEN	15x3 = 45	Mc-M-Mc	2013
	Debrecen	Local Goverment of Debrecen City of Country Rights DKV Debreceni Közlekedési Zrt	HUNGARY	18+5=90	C-S-R-S-C	2012
	Houston	Metropoloitan Transit Authority of Harris County (METRO)	USA	39+3=117	Mc-M-Mc	2014
	Birmingham Tram	West Midlands Passenger Transport Executive	UK	19*3=135	MC-S-T-S-MC	2014
	Cuiaba Tram	SECOPA	BRAZIL	40X7=280	Mc-S-M-S-T-S-Mc	2014

Articulated Units – Streetcars



PROJECT

Valencia Tramway – 70% Low Floor

Customer

Ferrocarril Generalitat Valenciana

Country

Spain

Number of Cars **48**

36 (12 articulated units of 3 cars)

12 (4 articulated units of 3 cars)

Structure

Mc-T-Mc

Deliveries

1993-1994
1999

Articulated Units – Streetcars

PROJECT

Lisbon Tramway - 70% Low Floor

Customer

Carris

Country

Portugal

Number of Cars 18

18 (6 units of 3 cars)

Structure

Mc-T-Mc

Deliveries

1995

Articulated Units – Streetcars

PROJECT

Bilbao Tramway – 70% Low Floor

Customer

Euskotren

Country

Spain

Number of Cars **24**

21 (7 units of 3 cars)

3 (1unit 100% LFT of 3 cars)

Structure

Mc-T-Mc

Deliveries

2002-2004

Articulated Units – Streetcars

PROJECT

Vélez-Málaga Tramway
100% Low Floor

Customer

Vélez Málaga Tramway

Country

Spain

Number of Cars **15**

15 (3 Tramwyas of 5 cars)

Structure

Mc-T-T-T-Mc

Deliveries

2006

Articulated units

PROJECT

Metro Centro Sevilla

Customer

TUSSAM

Pays

Spain

Nº of cars **25**

25 (5 trains of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2008

Articulated Units – Light Metro

PROJECT

Sevilla LRV - 100% Low Floor

Customer

Metro Sevilla

Country

Spain

Number of Cars **85**

85 (17 LRVs of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2008

Articulated Units – Streetcars

PROJECT

Vitoria Tramway - 100% Low Floor

Customer

Vitoria Tramway (Euskotren/Euskotram)

Country

Spain

Number of Cars 55

55 (11 Streetcars of 5 cars)

Structure

Mc-T-T-T-Mc

Deliveries

2008-2009

Articulated Units – Streetcars

PROJECT

Antalya Tramway

Customer

Antalya Metropolitan Municipality

Country

Turkey

Number of Cars 70

70 (14 Streetcars of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2008-2009

Articulated Units – Streetcars

PROJECT

Edinburgh Tramway

Customer

Tie Ltd.

Country

United Kingdom

Number of Cars 189

189 (27 Streetcars of 7 cars)

Structure

Mc-S-T-S-M-S-Mc

Deliveries

2010-2011

Articulated Units – Streetcars

PROJECT

Zaragoza Streetcars

Customer

SEM (Traza + Ayuntamiento Zaragoza)

Country

Spain

Number of Cars 105

105 (21 Streetcars of 5 cars)

Structure

C-S-R-S-C

Deliveries

2010-12

Articulated Units – Light Metro

PROJECT

Málaga LRV - 100% Low Floor

Customer
Malaga LRV

Country
Spain

Number of Cars 70
70 (14 LRVs of 5 cars)

Structure
MC-S-T-S-MC

Deliveries
2011-2012

Articulated Units – Streetcars

PROJECT

Belgrado Tramway

Customer

GSP

Country

Serbia

Number of Cars **150**

150 (30 units of 5 cars)

Structure

Mc-S-T-S-M

Deliveries

2011-2012

Articulated Units – Streetcars

PROJECT

MetroCentro Sevilla EXTENSION

Customer

TUSSAM

Country

Spain

Number of Cars 20

20 (4 units of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2011

Articulated Units – Streetcars

PROJECT

Granada Tramway

Customer

Ferrocarriles de la Junta de Andalucía

Country

Spain

Number of Cars 65

65 (13 units of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2012

Articulated Units – Streetcars

PROJECT

Tramway de Nantes

Customer

Nantes Métropole

Country

France

Number of Cars 60

40 (8 units of 5 cars)

20 (4 units of 5 cars)

Structure

Mc-S-T-S-Mc

Deliveries

2012

Articulated Units – Streetcars

PROJECT

Besançon Tramway

Customer

Communauté d'agglomération du grand Besançon

Country

France

Number of Cars 57

57 (19 units of 3 cars)

Structure

Mc-S-Mc

Deliveries

2013-2014

Articulated Units – Streetcars

PROJECT

Stockholm Tramway

Customer

Storstockholm Lokaltrafik AB (SL AB)

Country

Sweden

Number of Cars 73

45 (15 units of 3 cars)

28 (7 units of 4 cars)

Structure

Mc-M-Mc

Deliveries

2013-2014

Articulated Units – Streetcars

PROJECT

Tram Debrecen

Customer

- Local Government of Debrecen City of County Rights DKV Debreceni Közlekedési Zrt

Country

Hungary

Number of Cars 90

90 (18 Streetcars of 5 cars)

Structure

C-S-R-S-C

Deliveries

2013 - 2014

Articulated Trains – Streetcars

PROJECT

Houston LRV

Client

Metropoloitan Transit Authority of
Harris County (METRO)

Country

United States

Nº of cars 117

117 (39 trams of 3 cars)

Estructure

Mc-T-Mc

Delivers

2013-2014

Articulated Units – Streetcars

PROJECT

Birmingham Tramway

Client

West Midlands Passenger Transport Executive

Country

Unated Estates

Nº of cars **100**

100 (20 trains of 5 cars)

Estructure

Mc-S-T-S-Mc

Delivers

2014

Articulated Units – Streetcars

PROJECT

Cincinnati

Client

City of Cincinnati

Country

USA

Nº of cars

5 (3M) cars Base + 25 Optional

Estructure

Mc-T--Mc

Delivers

2015

Articulated Units – Streetcars

PROJECT

Cuiaba Tramway

Client

SECOPA (Secretaria Extraordinaria da Copa do Mundo FIFA 2014)

Country

Brazil

Nº of cars **280**

280 40 trains of 7 cars)

Estructure

Mc-S-M-S-T-S-Mc

Delivers

2014

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1 INTRODUCTION 2

1 INTRODUCTION

The purpose of this document is to answer the questions regarding the ACR Freedrive equipment for Washington DC Streetcar.

2 QUESTIONS & ANSWERS

Question #1

The District will consider designs which allow for the use of an in-street conductor which supplies power to the vehicle continuously while operating, a system with long gaps in the overhead supply and wired areas for recharging while operating (batteries), or a system which charges an on-board storage system only when stopped at station platforms (supercapacitors or flywheels). Which of these types of systems have you supplied vehicles (rail, bus, or other transport) for? Or, are in the process of supplying? Do you have any comments on the advantages or disadvantages concerning the three system types?

Answer #1

CAF has developed **its own concept** of equipment for energy efficiency and catenary free operation for streetcars.

The concept of this system proposed by CAF is the result of a long process of analysis, research and development.

CAF was looking for a solution that could provide both a high energy efficiency by recovering as much as braking energy from the train as possible and also enable the operation of the train without overhead lines.

CAF studied the different possibilities for energy efficiency and catenary free operation summarized in the following table:

			Features							
			Infrastructure Cost	**Life Cycle Cost**	**Availability**	**Safety**	**Energy recovery**	**Catenary free**	**Energy Transmission Efficiency**	**Provider dependency**
Energy Efficiency and Catenary Free Technologies	**Third Rail**	**Standard Third Rail**	Low	Low	High	Low	-	Yes	High	Low
		Controlled Third Rail	High	High	Low	Medium	-	Yes	High	High
		Inductive	High	High	Low	High	-	Yes	Low	High
	Reversible Substation		High	Medium	High	High	High	No	High	Low
	Energy Storage	**Infrastructure**	Medium	Medium	High	High	High	No	High	Low
		Onboard	Low	Medium	High	High	High	Yes	High	Low

As a result CAF selected the **on-board energy storage concept** as it is the most competitive solution, with low infrastructure costs, to provide both a high energy efficiency and catenary free operation.

Also regarding the technology to be used CAF completed a rigorous study and comparison summarised in the following table:

Features

On-board Energy Storage System	**Life Cycle Cos**	**Energy density**	**Power**	**Fast charging**	**Availability**	**Safety**	**Maturity**
Fuel-cell (Hydrogen)	Low	High	Medium	Yes	Medium	Low	Low
Flywheel	Medium	Low	High	Yes	Medium	Medium	High
Batteries	Medium	High	Low	No	High	High	High
Ultracaps	Medium	Medium	High	Yes	High	High	High
Hybrid solution (UCs+Batts)	Medium	High	High	Yes	High	High	High

Fuel-cell technology was discarded because it is not mature enough for its application in the railway market, although it can be a promising technology for the future.

Flywheel technology was discarded for its low energy density and availability (mechanical system with complex integration) and safety issues.

Finally, CAF selected the **ultracaps** the only one to provide high power, fast charging, and good availability and safety characteristics. Ultracapacitors have medium energy density so CAF is also integrating **battery technology** to increase the energy capacity of the energy storage system and also, depending on the service, the batteries are sufficient to provide catenary free operation mode.

Ultracaps and batteries, even if they are mature proven technologies, are in constant evolution driven by the automotive industry, so there are **good expectations for** improvements on that technology and **significant reduction of costs**.

The energy storage system designed by CAF is called “**ACR Freedrive**” when the goal is catenary free operation mode, and “**ACR Evodrive**” when the focus is Energy Recovery. Both systems are **based on a fast charging process** in the train stations at the stops of the train with the main advantage of **very low costs on the infrastructure**.

The ACR Freedrive system is **modular** (up to 5 independent packs of ultracapacitors or batteries for each system), **configurable** (number of ultracapacitor and battery packs depending on the power/energy needed in each application) and **redundant**.

Question #2

A traditional streetcar is designed to operate from an overhead supply system operating continuously at either 600 or 750 Vdc. Would your company’s offering place any special or *additional requirements concerning integration of the electrification system? Would your technology operate with a pantograph when not on a wireless section?*

Answer #2

The ACR Freedrive system is capable to operate with both 600 and 750 VDC nominal catenary voltage with voltage variations indicated in IEC 60850 standard.

Question #3 - In Street Conductors

Has the in-street conductor been utilized in areas which normally experience snow and ice in the winter? What material would you use for fabricating in-street conductors? Would the material show corrosion for the application of de-icing road salt? What provisions are made to prevent snow plow blades from damaging the rail?

Answer #3

CAF has not developed an in-street conductor system for catenary free operation mode.

Question #4 – In Street Conductors

Has the in-street conductor been installed in mixed use traffic lanes? Has it been installed in reserved lanes with normal traffic operating at right angles across it? Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

Answer #4

CAF has not developed an in-street conductor system for catenary free operation mode.

Question #5 – In Street Conductors

How is the conductor installed in the street? Are there any restrictions on horizontal or vertical curvature of the pavement? How are crossings or turnouts implemented with the conductor rail? What clearances are required for other structures such as manholes and metallic covers?

Answer #5

CAF has not developed an in-street conductor system for catenary free operation mode.

Question #6 – Batteries

Which battery type do you have experience in applying, Lithium (Li) or Nickel Metal Hydride (NiMH)? What is the maximum acceleration rate and maximum speed normally used in these applications?

Currently, Nikel Metal Hydride batteries are used for ACR Freedrive system.

Usually, the maximum speed in catenary free operation zones is lower than the maximum service speed as those zones are usually located in historical and pedestrian areas.

Question #7 – Batteries

What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

Answer #7

The charge and discharge levels of the batteries are directly related with the service life of the batteries.

In order to minimize the impact of the charge and discharge cycles in the battery life, for a normal operation mode, the DOD (Depth of Discharge) of the batteries depends on the operation condition of each solution but it should be around 10-25%.

The ACR system (developed by CAF) is composed by a DC/DC converter which manages the charge and discharge of the batteries.

The battery cells are grouped into modules. These modules are monitored (with temperature and voltage) in order to adapt and manage properly the charge and discharge cycles of the batteries depending on the reading values.

Question #8 – Batteries

The operating environment in DC has a temperature range of -15°F to 106°F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

Answer #8

When outside temperature is below 32ºF, a pre-heating of the batteries is needed. The pre-heating of the batteries can be made charging and discharging the batteries before the streetcar starts the service. In this way, the batteries are self-heated.

Another way for pre-heat the batteries is to install a heating cable in the air inlet of the battery module. In this way, when the battery module is forced cooled, the batteries are heated by the warm surrounding air.

As low temperatures, high temperatures affect the life of the battery. In order to mitigate these effects, the tops of the ACR box are protected against the solar radiation. Moreover, as mentioned above, the ACR system adapts the charge and discharge cycle of the batteries depending of the temperature of the batteries.

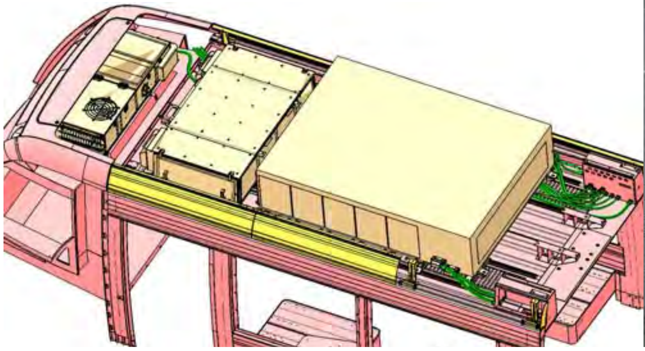
The forced air cooling is used for cooling the battery modules.

Question #9 – Batteries

There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

Answer #9

The ACR system is equipped on the roof of the streetcar as shown below.
The car builder designs the roof equipment in order to avoid the impact from traffic accidents and preserve passenger safety.



The batteries equipped in the ACR system are NiMh type. This type of battery is less sensitive to flammability than lithium battery. Nevertheless both battery modules and ACR box comply with ENFF 16101 and ENFF 16102 standards and mechanically robust complying with CEI-IEC 61373 (ver.2010) - Impact and Crash test standard.

Question #10 – Batteries

Batteries will be discharged during overhead gaps and recharged while operating in wired sections. As a "ball-park" approximation, if a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge? What would be the maximum current draw for battery recharging?

Question #11 – Batteries

If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106°F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160°F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

The analysis should be done, taking into account wire sections and the consumed current.

For the stationary case, the current is regulated in each case, depending on the situation that the train will be stopped or not.

Question #12 – Supercapacitors

What is the time required to recharge fully depleted supercapitors at a stop? What level of current and voltage is this time based on?

Answer #12

The power required by the ACR equipment in a charging point depends basically on two parameters:

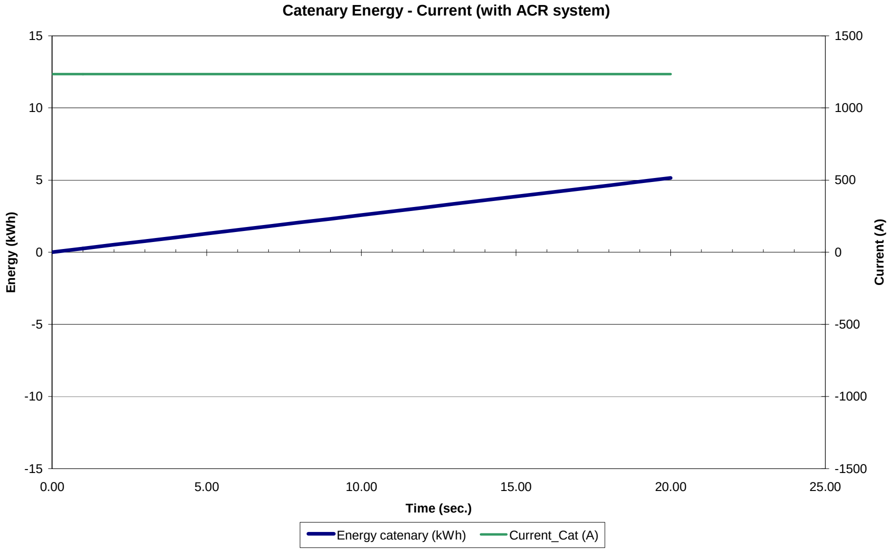
- Energy to be charged: After a catenary free zone, in order to fully charge the ACR equipment, it is necessary to recharge the energy in the charging point. This energy corresponds to the energy consumed in the catenary free zone.

- Charging time: Depends on the dwell time at stations. The ultrafast charge is performed while the passengers enter and leave the streetcar.

Average power = (Energy) / (Charging time)

For reference, to get an idea of the level of expected charging current, attached below catenary current values defined for the Zaragoza streetcar (streetcar of 32 meters).

- Ultrafast charging maneuver: 1300-1400A during 20 seconds



Question #13 – Supercapacitors

For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

Answer #13

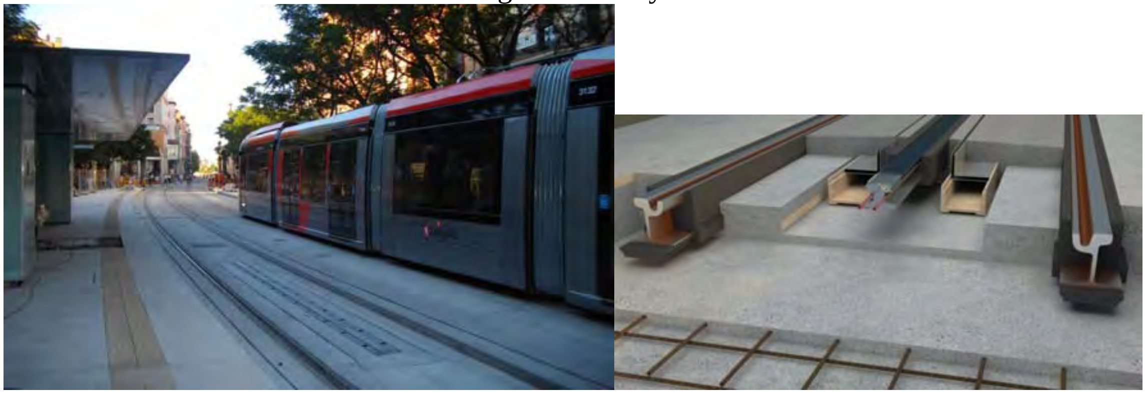
It is understood "discrete charging system" as ultrafast charging process.

When the streetcar has to run through 2 consecutives catenary free zones, an ultrafast charging point is needed between both zones in order to charge the ACR equipment (if the equipment does not have enough energy to run catenary free through both zones).

The ultrafast charging process can be performed either from overhead catenary system or from ground system.

- The overhead catenary system consists of a short rigid catenary installed at the stops. The energy capture is made with a pantograph as shown below. This is a service proven solution in Seville catenary free streetcar. (2 + years in service)

- The ground system consists of a third rail which is powered only when the vehicle is over the rail. The energy capture is made with a shoes located in the bogie.as shown below. This solution is in service in Zaragoza catenary free streetcar.



Question #14 – Supercapacitors

If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

Question #15 – Batteries & Supercapacitors

Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Answer #15

The sizing of the ACR system is always prepared under non-favorable simulation conditions (high loads, high accelerations/decelerations, etc…). This guarantees correct operation, with an appropriate safety margin, under normal operating conditions.

The system also includes intelligent available energy control systems to deal with any operating fault that could occur. In other words, if the train has route problems resulting in a delay (e.g. traffic jams, unforeseen (emergency) braking), the system can request that the train reduces the train performance as a preventative measure to prevent energy deficits in a specific section.

The definition and adjustment require that the preventive measures be prepared during project phase, performing a more detailed study of the route and final design of the train. In short, the preventative and corrective measures are as follows:

Preventative measures	Activation conditions:
(1) Consumption charge reduction request (mainly HVAC).	**(1) (2)** Activated when the energy level of the ACR units is less than a critical level defined for the route.
(2) Maximum train speed limit	
Corrective measures	**Activation conditions:**
(3) The use of the backup energy from the supercapacitors to reach the next stop	**(3)** This is activated when the useful energy of the ACR equipment runs out. In this case there is an extra 33% of energy that can be used under reduced power conditions in order to reach the next stop. Use of the supercapacitor backup energy is relegated to being used when the previous preventative measures have been applied but have not succeeded to prevent the ACR unit useful energy from running out.

The ACR equipment can be equipped with a battery module. In case of the backup supercapacitor energy is not enough for reaching the next charging point; the battery energy can be used as backup.

Question #16 – Vehicle Design Criteria

The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

Answer #16

Not Applicable

Question #17 – Vehicle Design Criteria

The District's current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

Answer #17

The ACR equipment is modular and configurable. Thus, the required space for the energy storage system depends on the amount of energy installed in the ACR equipment. Depending on the customer requirements, it is necessary to perform simulations to correctly sizing the equipment.

Apart from the size of the ACR equipment, roof equipment distribution of the streetcar is required.

Question #18 – Retrofit of Existing Vehicles

The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

Answer #18

The ACR equipment is modular and configurable. Thus, the required space for the energy storage system depends on the amount of energy installed in the ACR equipment. Depending on the customer requirements, it is necessary to perform simulations to correctly sizing the equipment.

Apart from the size of the ACR equipment, roof equipment distribution of the streetcar is required.

Seville catenary free streetcar was the first streetcar equipped with ACR system (first prototype in revenue service). This streetcar was an existing train that was refurbished to implement the new system. In this case it was necessary to change some electrical equipment in order to optimize the roof distribution. Each case is however different and a specific study should be done for the required units to check the feasibility of a modernization.

Question #19 – Specialized Equipment

What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

Answer #19

For ACR maintenance purposes, the supercapacitor energy has to be discharged with a discharger cabinet, for safety reasons

In the case of the batteries, they can not be discharged in order to preserve their service life. But it is important to remark that those batteries has been designed to work in a very low voltage conditions (around 150 V)

Question #20 – Training and Education

Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a *typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?*

Answer #20

The ACR system does not need any special maintenance apart from the cleaning and checking of the cooling circuit. The maintenance of the DC/DC converter is similar to other electronic component and the supercapacitors and batteries must be treated as conventional capacitors and batteries.

Thus, it is not required and expert maintenance team for ACR equipment, and does not require specialized personnel for the maintenance,

On the other hand all the training and education for those systems, will be provided by the car builder

Alstom

APS SOLUTION

2013, March 8th

ALSTOM

AESTHETIC POWER SUPPLY – APS - Projects location

Tours
Sep 2013
21 trams
3.8km single track APS

Orléans
Since Jun 2012
21 trams
4.2km single track APS
60 000km run in APS

Reims
Since Apr 2011
18 trams
4,0km single track APS
370 000km run in APS

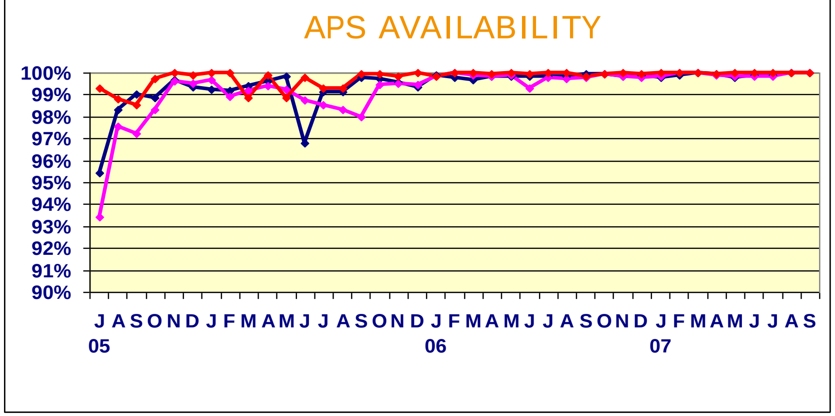
Total APS
188 trams (130 in service)
63km single track APS (39.2km in service)
12 300 000km run in APS

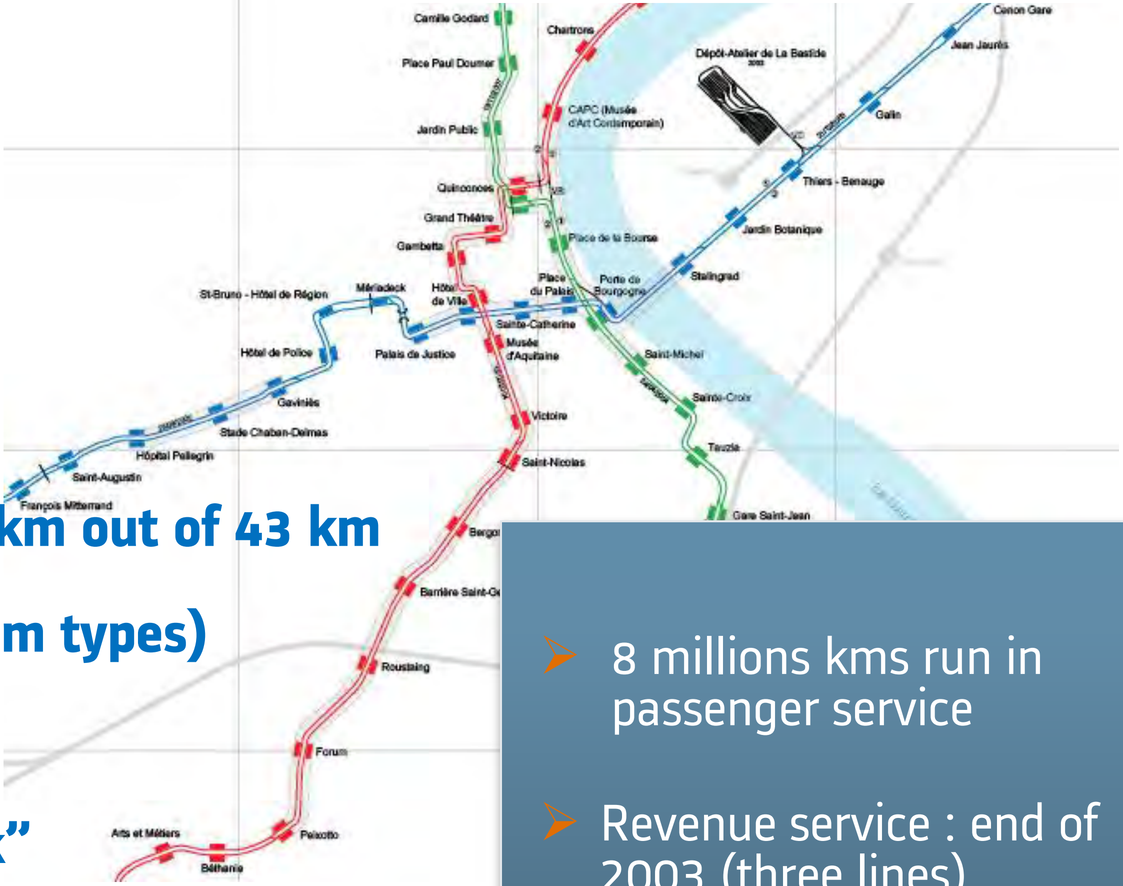
Angers
Since Jun 2011
17 trams
3.0km single track APS
165 000km run in APS

Dubaï
Nov 2014
11 trams
19km single track APS

Bordeaux
Since Dec 2003
100 trams (74 in service)
28km single track APS(27km in service)
11 700 000km run in APS

Bordeaux


APS AVAILABILITY

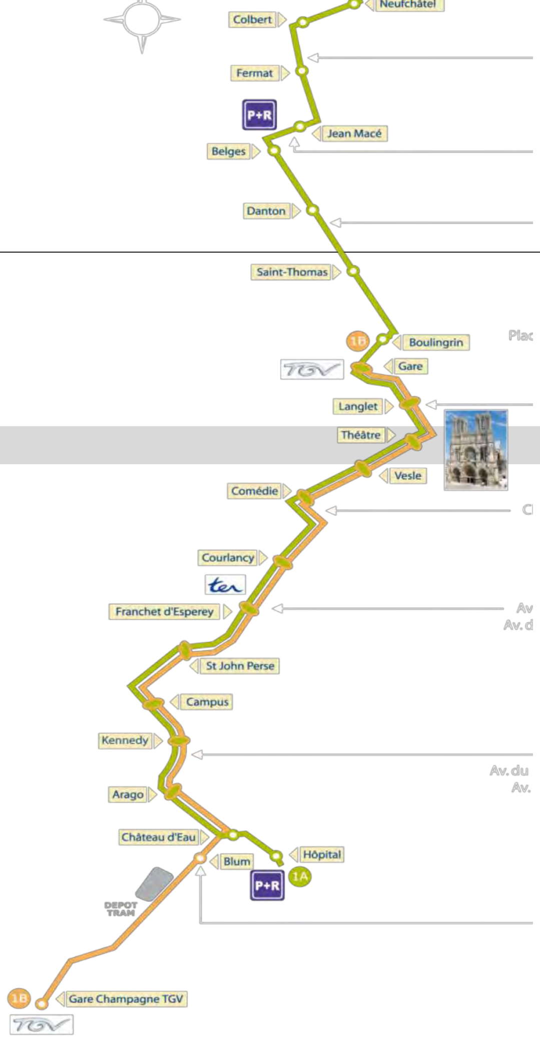


- **Proven solution : 13.4 km out of 43 km**
- **74 tramways (30 & 40 m types)**
- **No power restriction**
- **No risk of "empty tank"**
- **Complete intrinsic safety**

- 8 millions kms run in passenger service
- Revenue service : end of 2003 (three lines)

ALSTOM

Reims



- **Concession over 30 years**
- **2 km out of 12 km**
- **23 stations**
- **18 tramways**

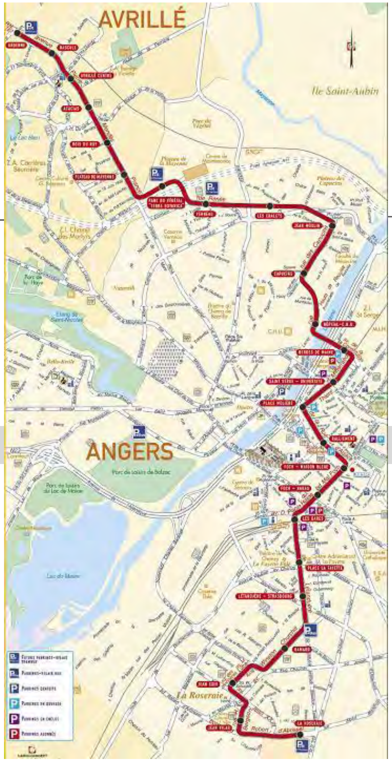
Project start in July 2006

1st Run : September 2010

Passenger service : April 18th 2011

Angers

- 1,5 km out of 12 km
- 25 stations
- 17 tramways



Project start in November 2006

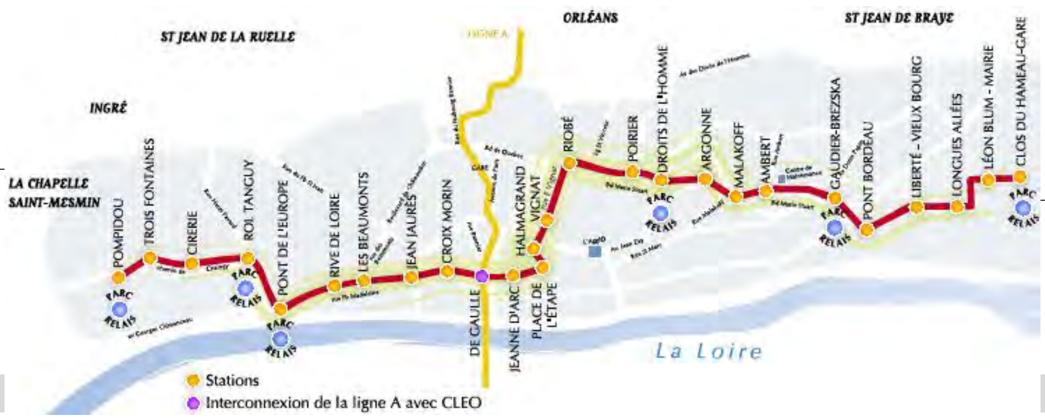
1st Run : December 2010

Passenger service : June 25th 2011

Particularity : 8% slope

TRANSPORT ALSTOM

Orléans



- **2,1 km out of 12 km**
- **25 stations**
- **21 tramways**

Project start in September 2006

Passenger service : End of June 2012

TRANSPORT ALSTOM

Tours

- 2 km out of 15 km
- 30 stations
- 21 tramways (43 m version)

Project start in Sept 2010

Passenger Service : Autumn 2013

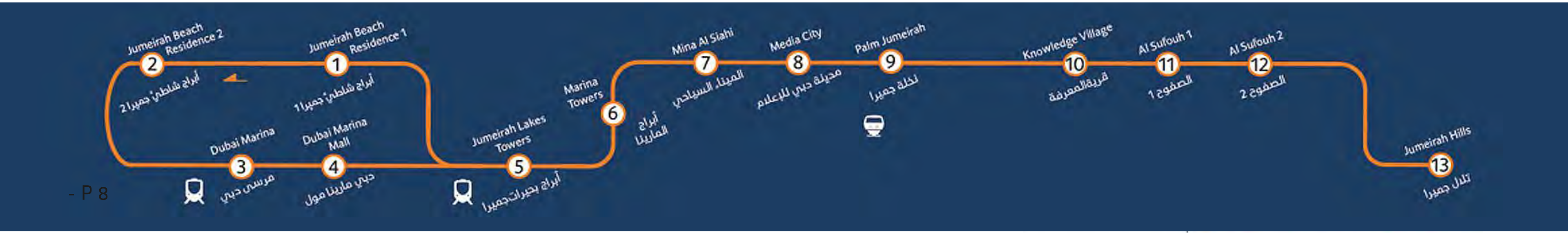
Dubai

The first city in the Gulf region to be equipped with a tramway transit system

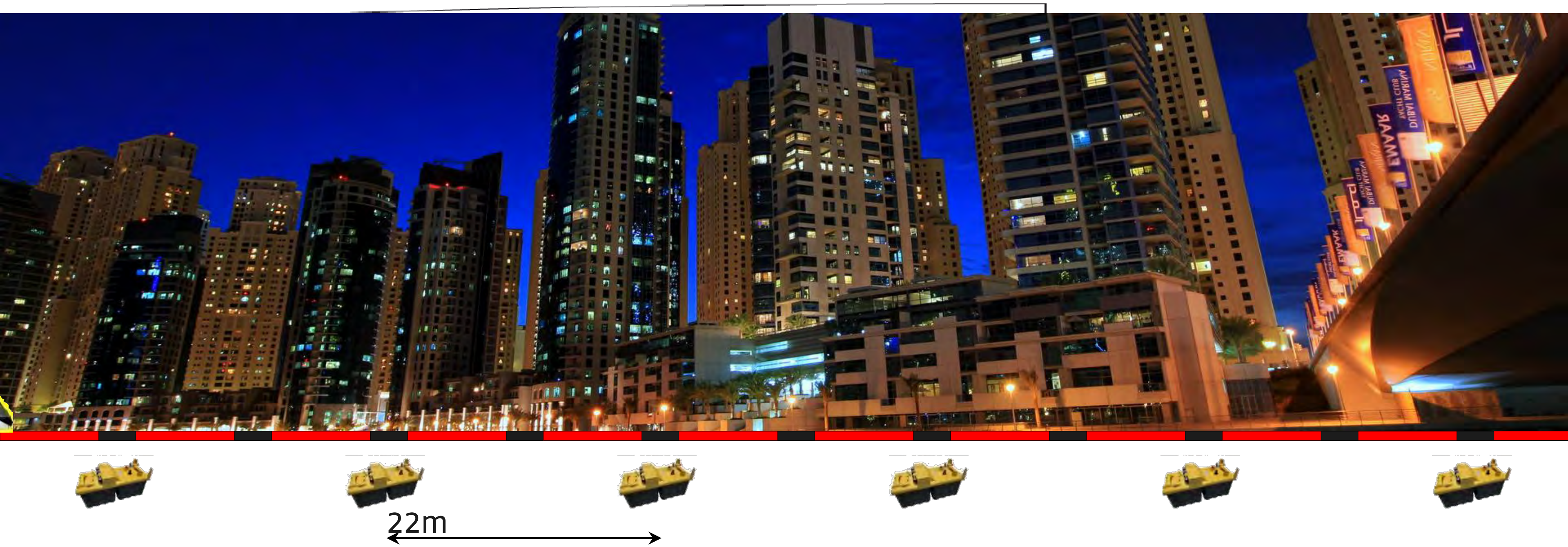
- **19 km fully catenaryless**
- **13 stations**
- **11 tramways (43 m version)**

Project start in June 2008

New Passenger Service : 2014



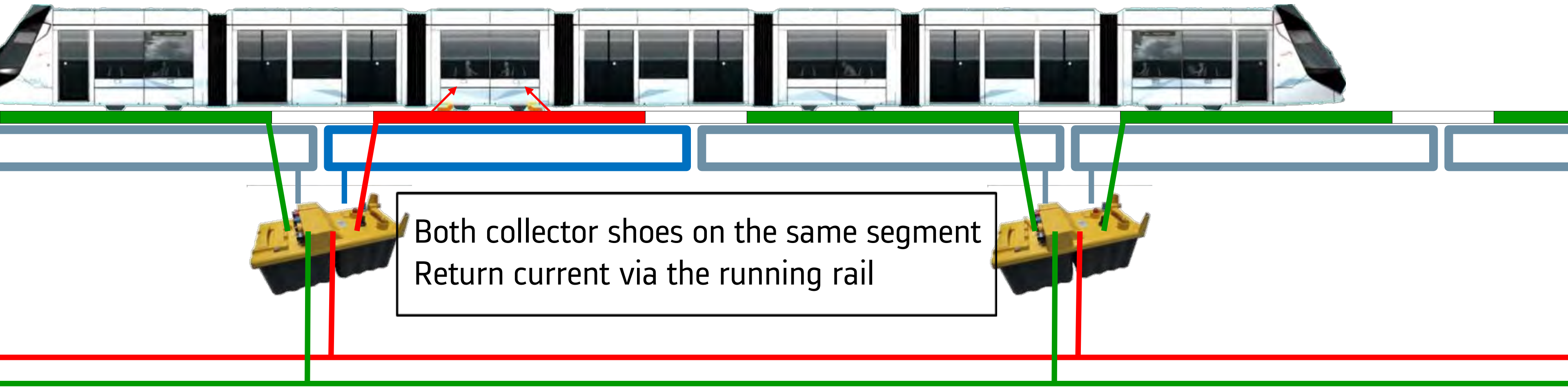
APS Basic Principle



- ✓ Period : 11m / Conductive Segment 8m / Neutral zone : 3m
- ✓ Each power box drives 2 segments, a power box every 22m
- ✓ Tramways are 30 or 40m long, covering every live segments
- ✓ After tram passage, the segment is connected to the rail voltage

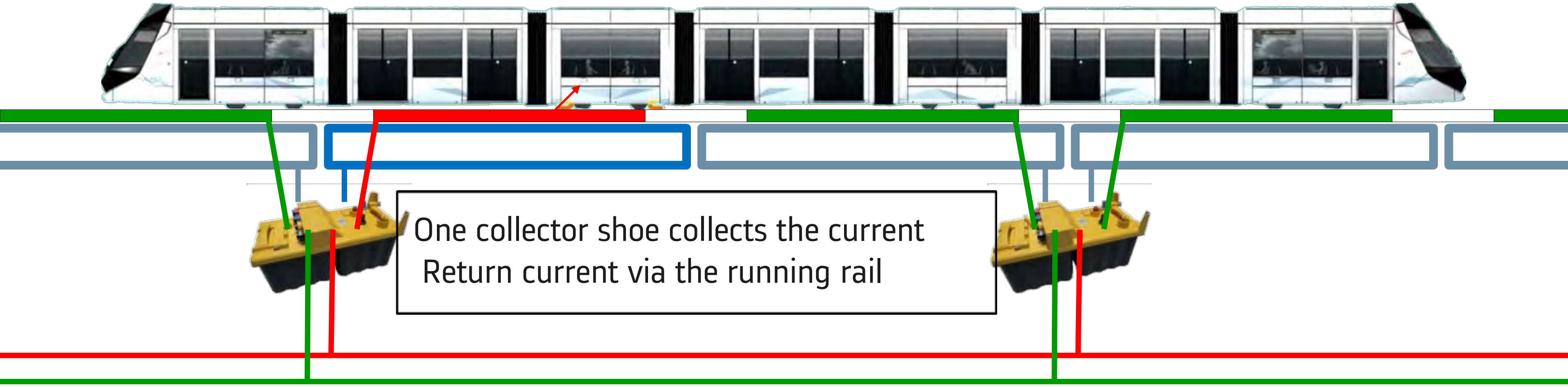
TRANSPORT ALSTOM

APS Basic Principle - distribution chronology



Both collector shoes on the same segment
Return current via the running rail

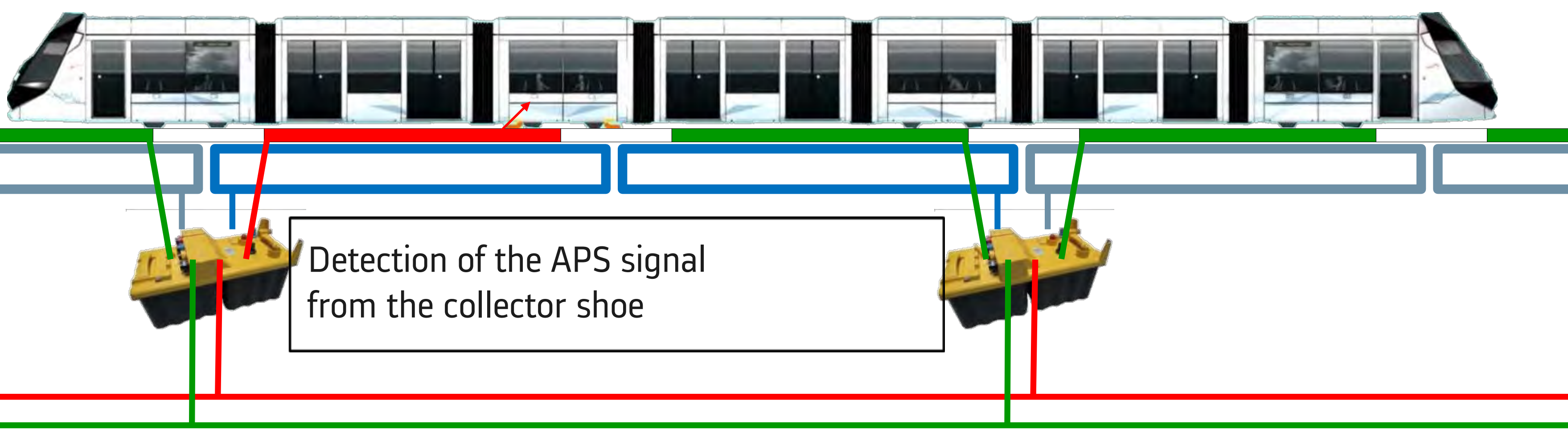
APS Basic Principle - distribution chronology



One collector shoe collects the current
Return current via the running rail

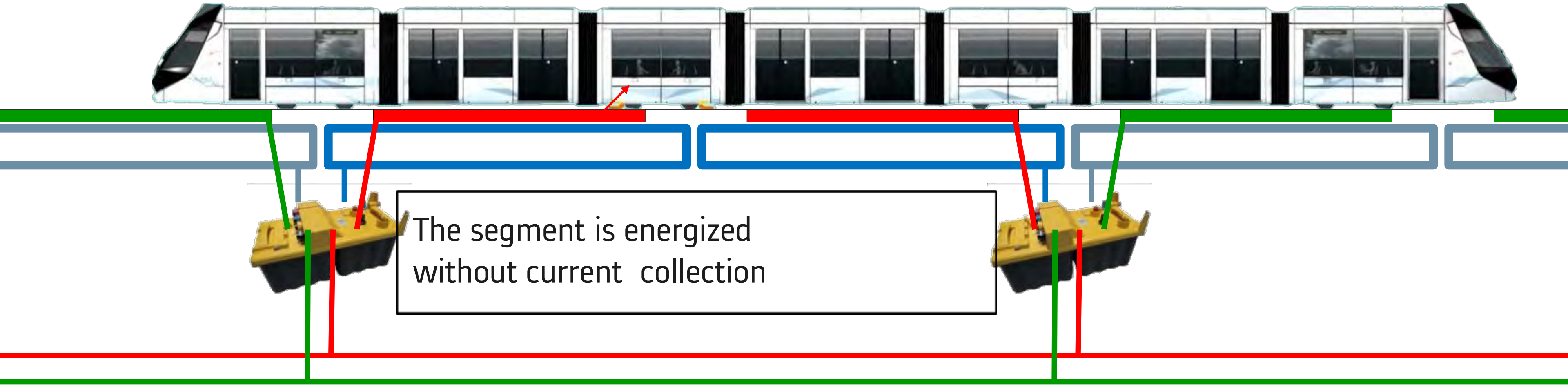
TRANSPORT ALSTOM

APS Basic Principle - distribution chronology



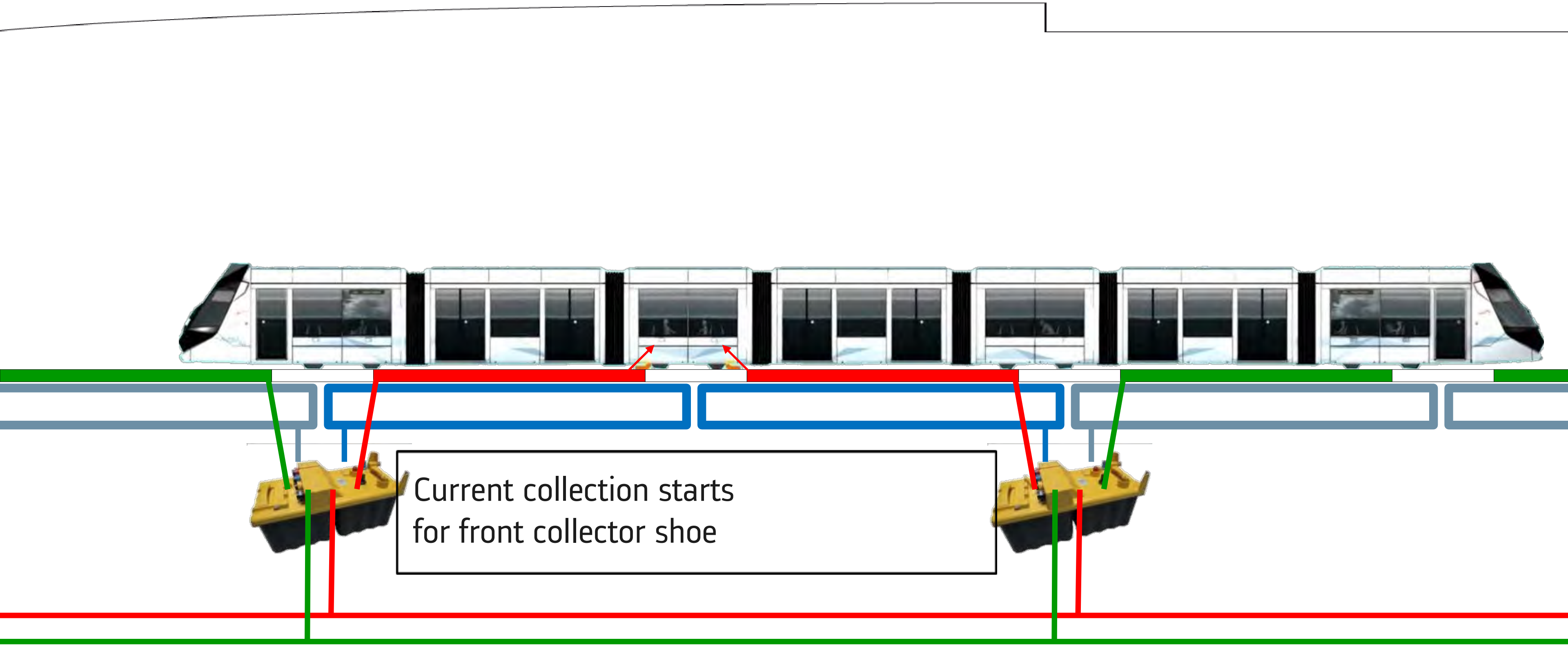
Detection of the APS signal from the collector shoe

APS Basic Principle - distribution chronology



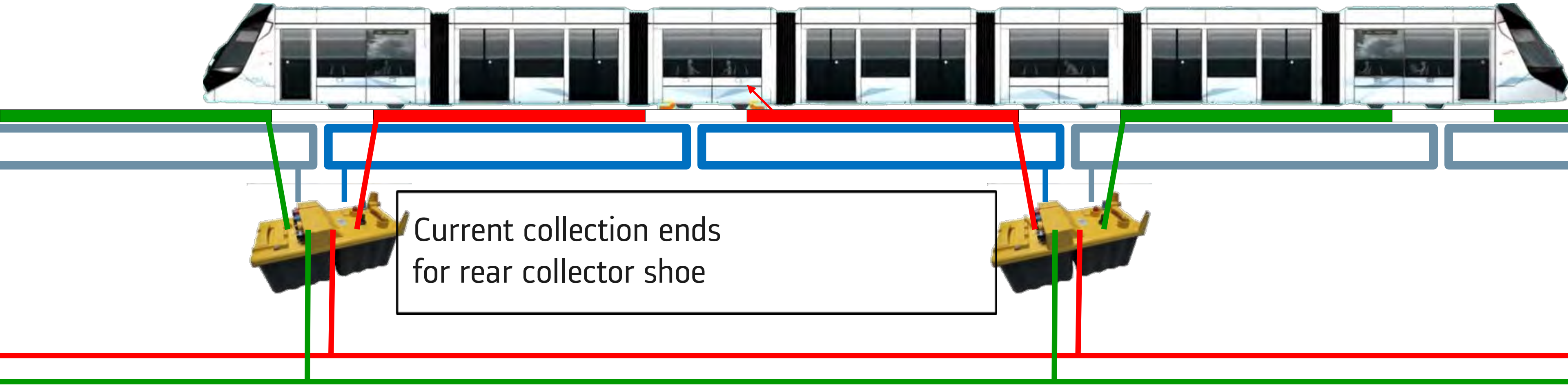
The segment is energized without current collection

APS Basic Principle - distribution chronology



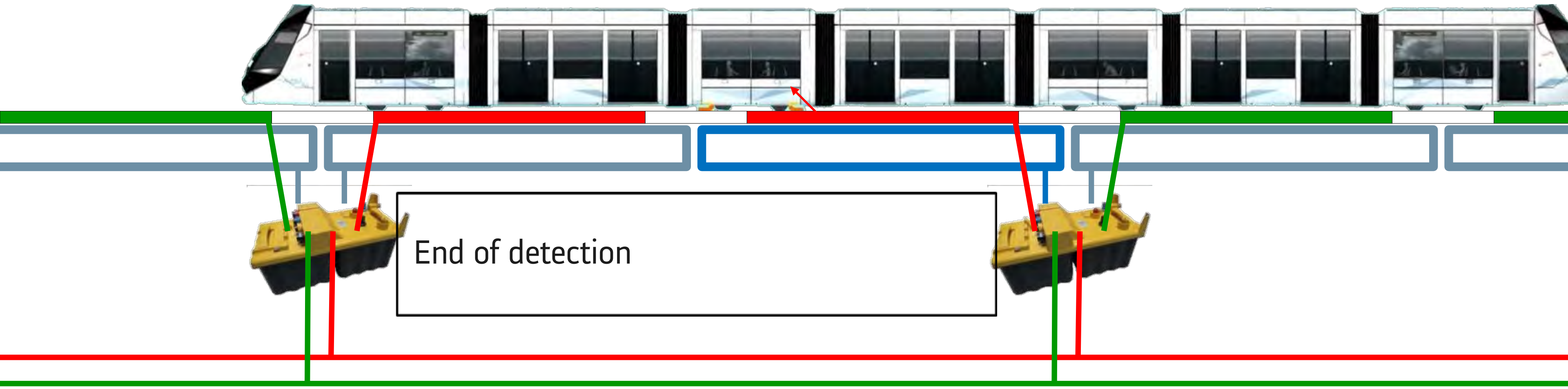
Current collection starts
for front collector shoe

APS Basic Principle - distribution chronology



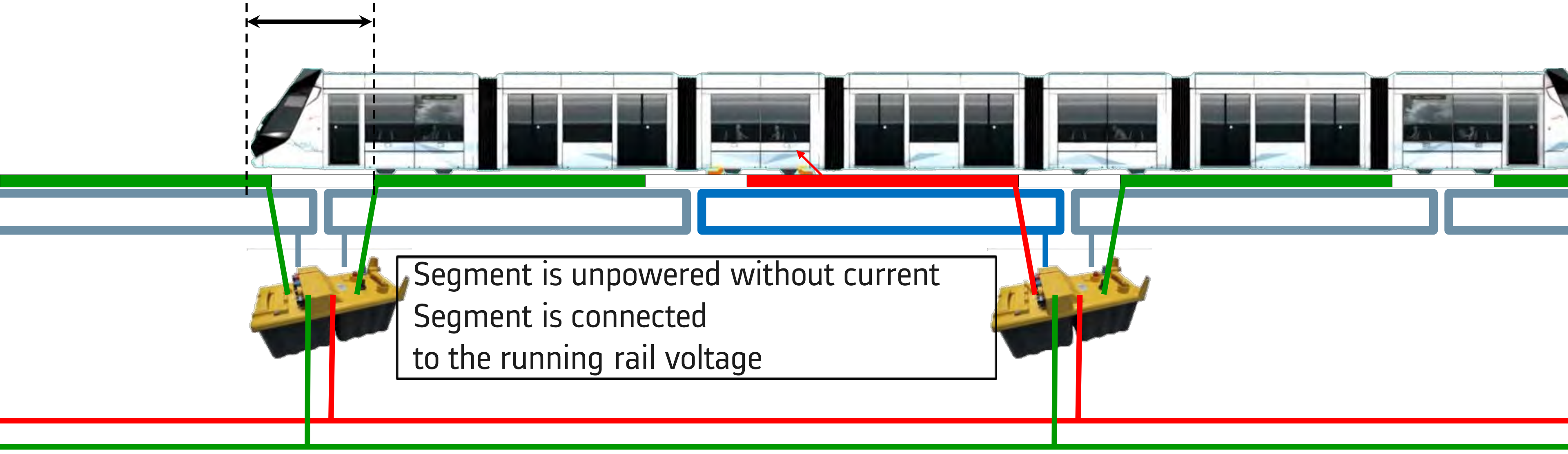
Current collection ends
for rear collector shoe

APS Basic Principle - distribution chronology



End of detection

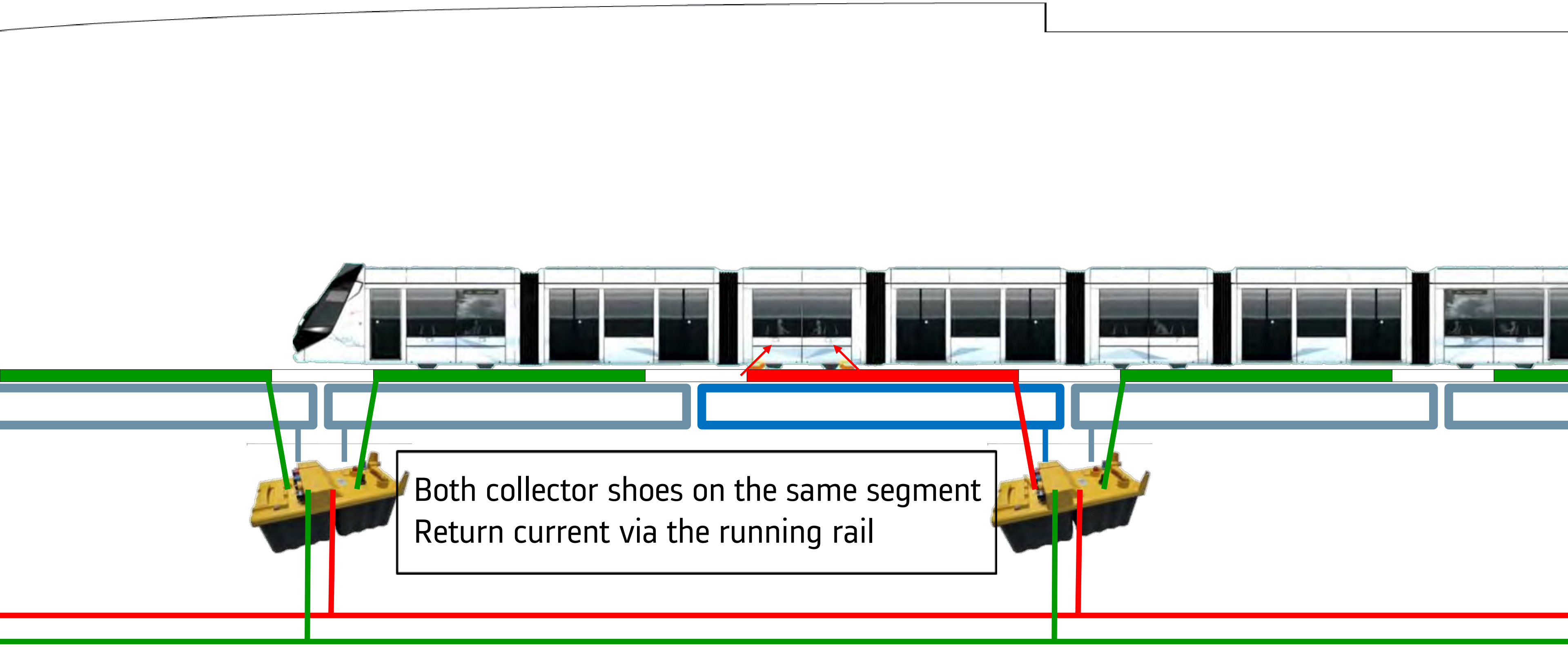
APS Basic Principle - distribution chronology



The tram still protects the segment

Segment is unpowered without current
Segment is connected
to the running rail voltage

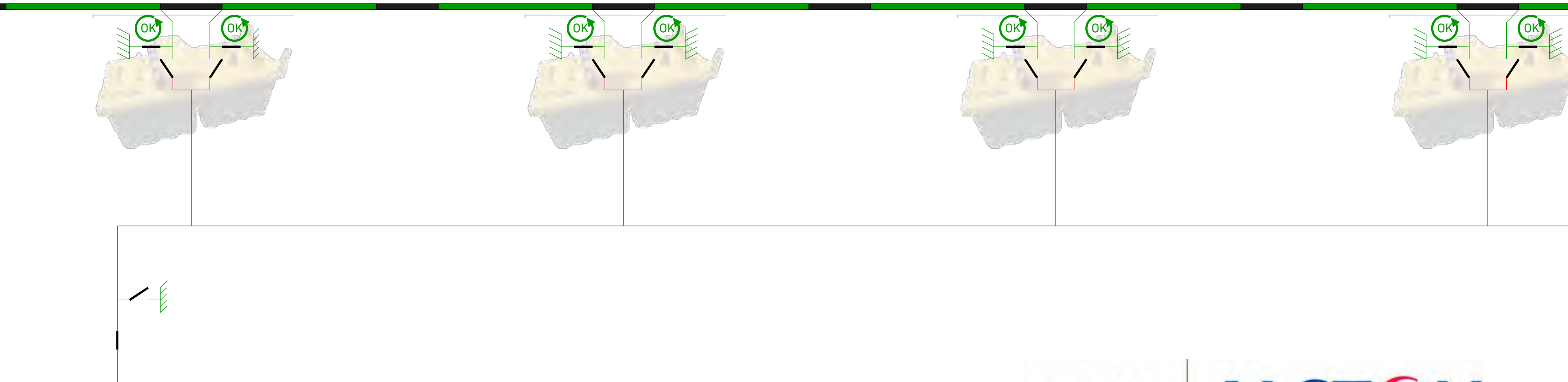
APS Basic Principle - distribution chronology



Both collector shoes on the same segment
Return current via the running rail

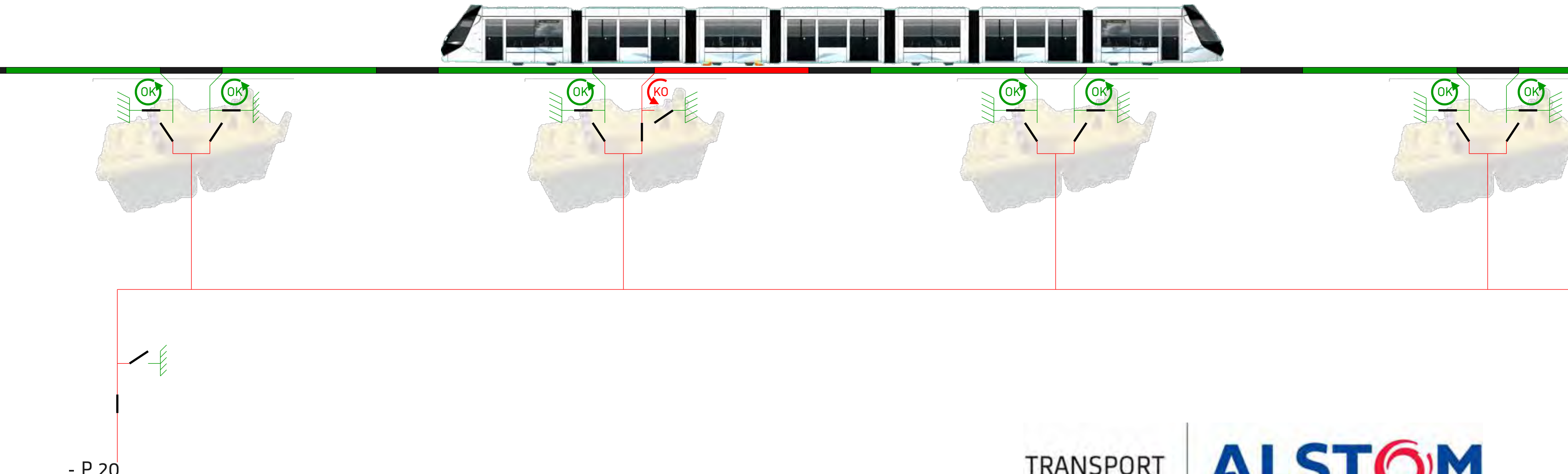
APS Basic Principle - Safety

- ✓Continuous and safety earthing verification
- ✓Static relays will not spontaneously close



APS Basic Principle - Safety

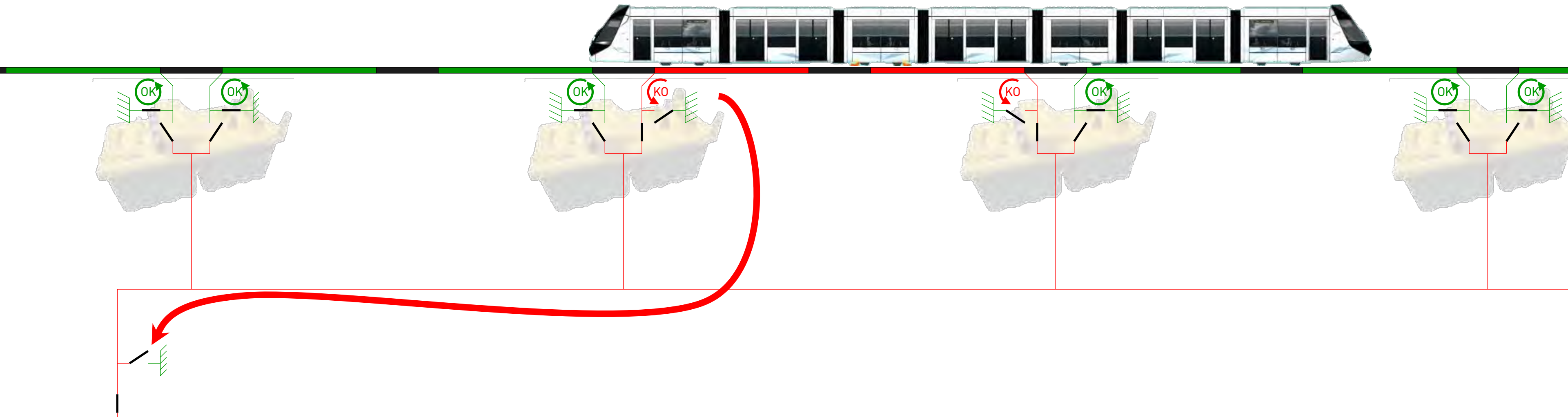
✓Lack of earthing during safety tramway detection is a normal status



TRANSPORT ALSTOM

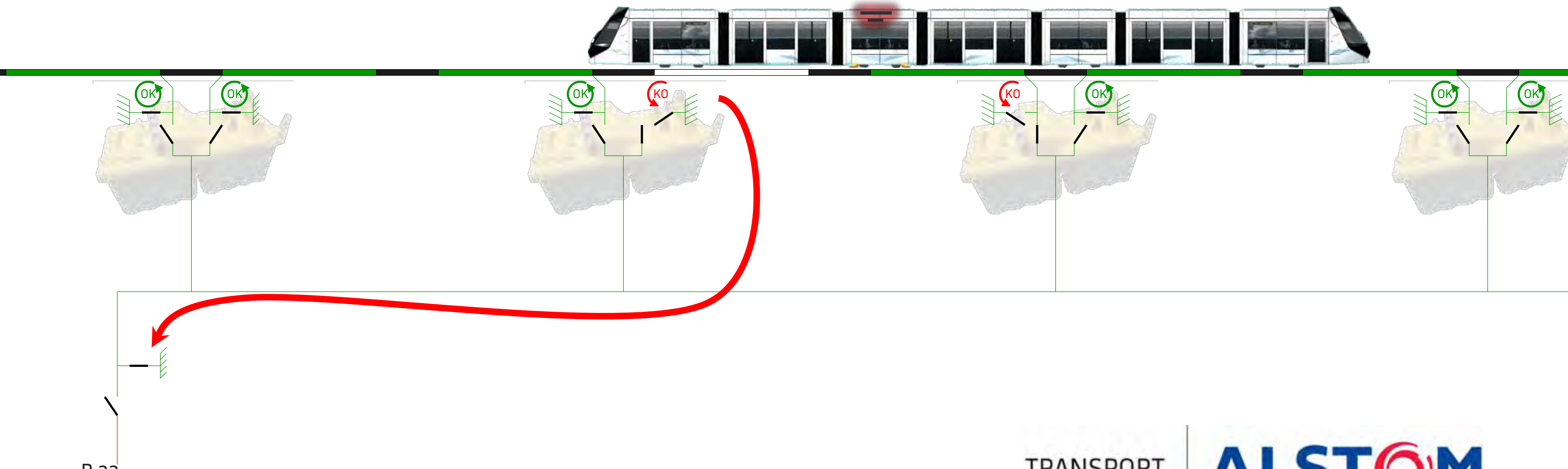
APS Basic Principle - Safety

- ✓Lack of earthing after tramway detection is a failure.
- ✓It is immediately and safely reported upstream (at the substation)



APS Basic Principle - Safety

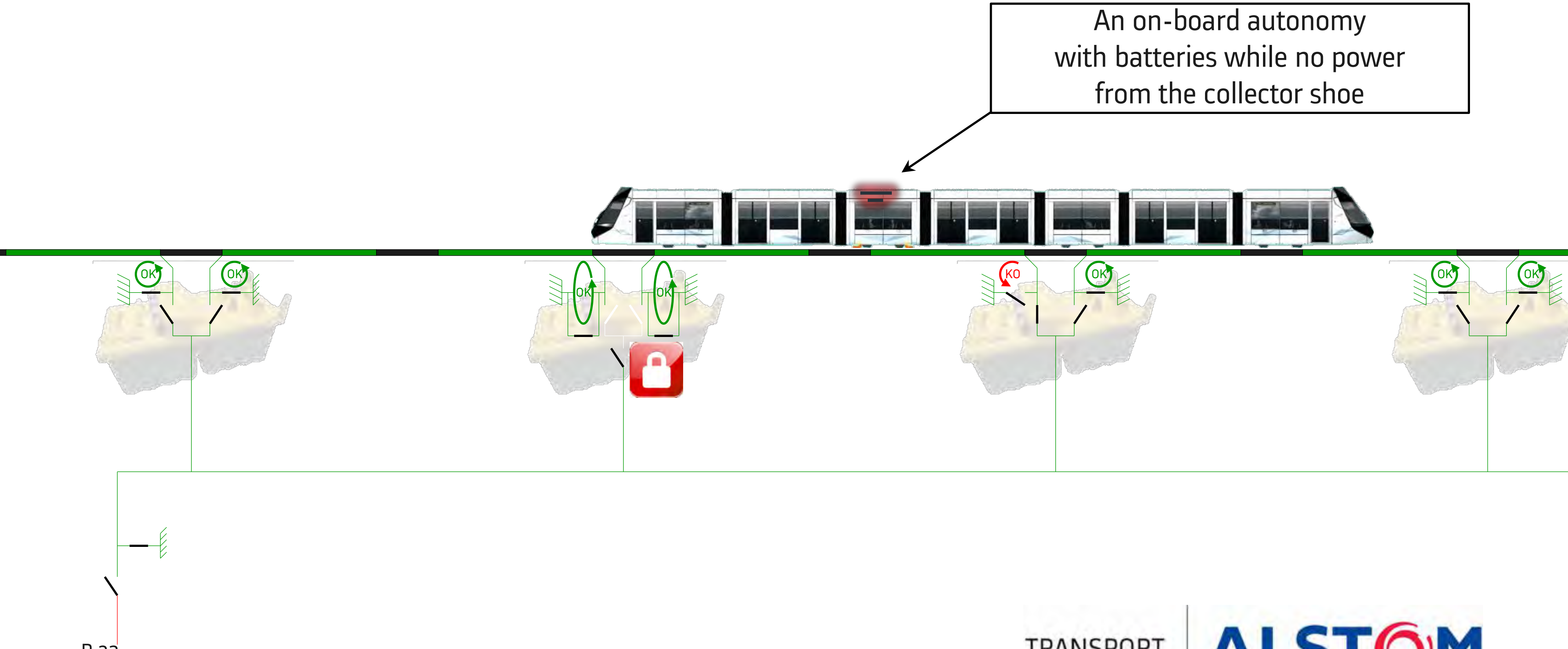
✓The total section is unpowered and set in safe and restrictive status.



An on-board autonomy
with batteries while no power
from the collector shoe

APS Basic Principle - Safety

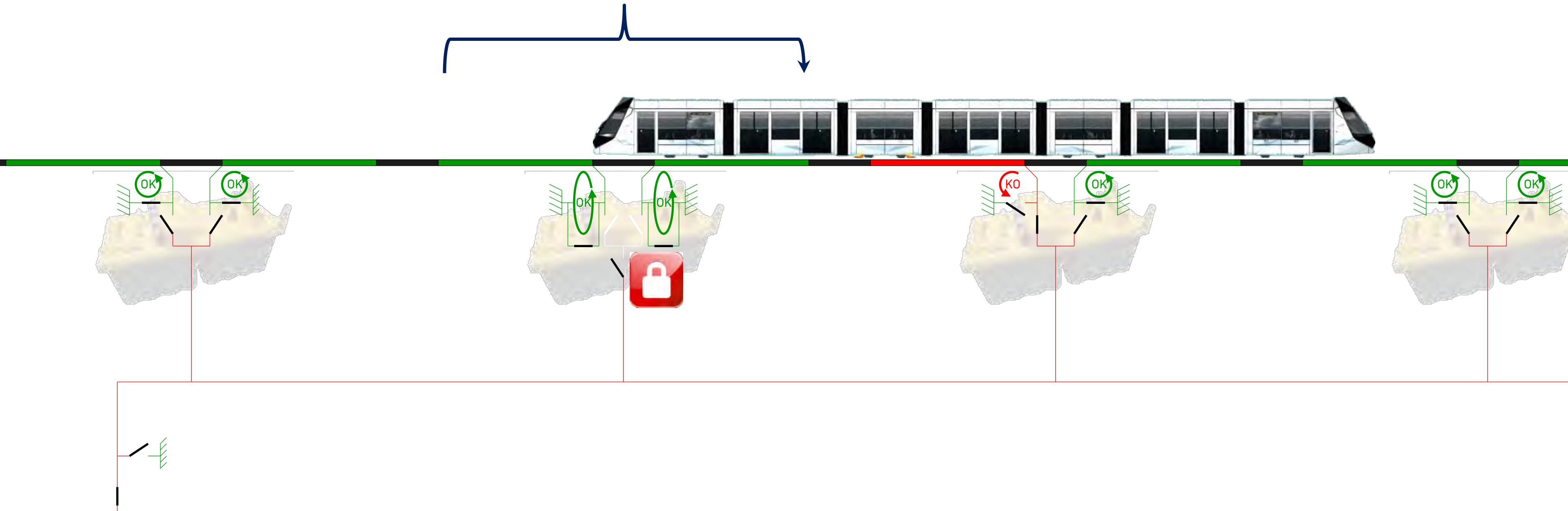
- ✓Automatic or remote isolation of the power box
- ✓Second safety earthing verification circuit in the power box



An on-board autonomy with batteries while no power from the collector shoe

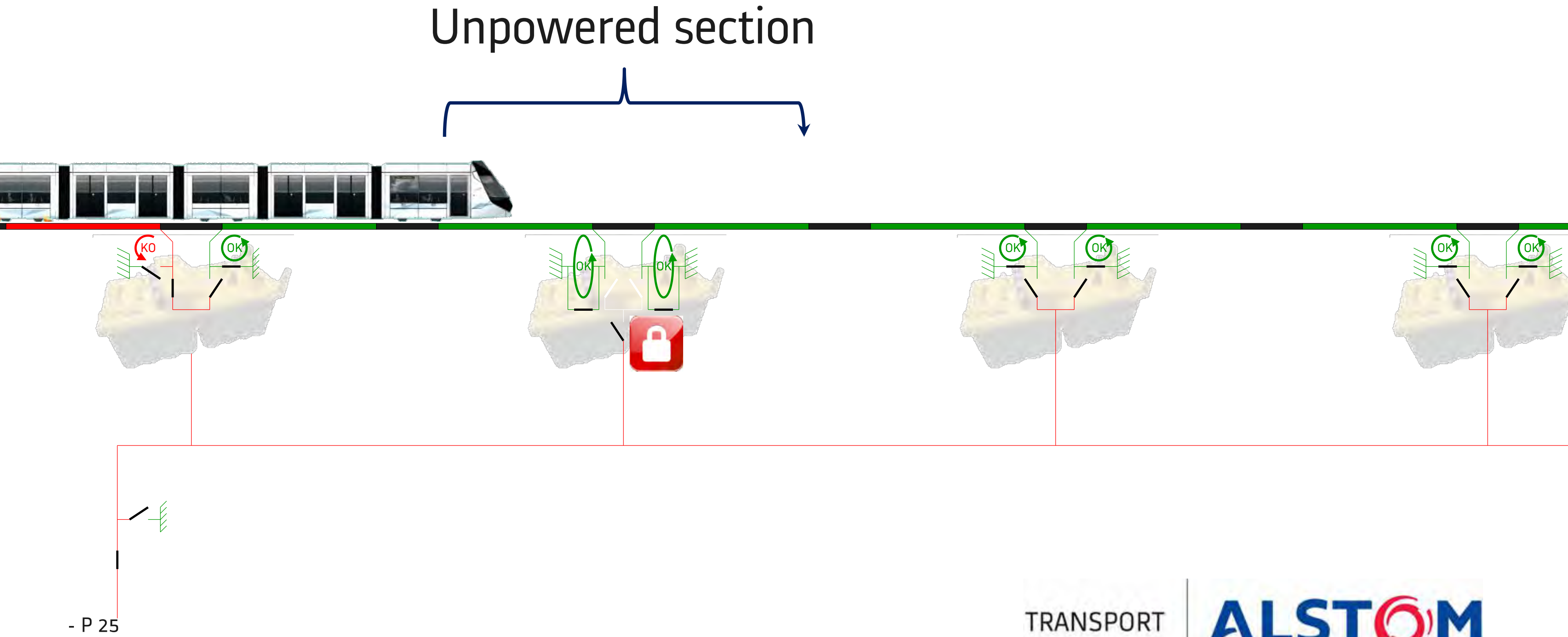
APS Basic Principle - Safety

The operation resumes with an isolated box


Unpowered section

APS Basic Principle - Safety

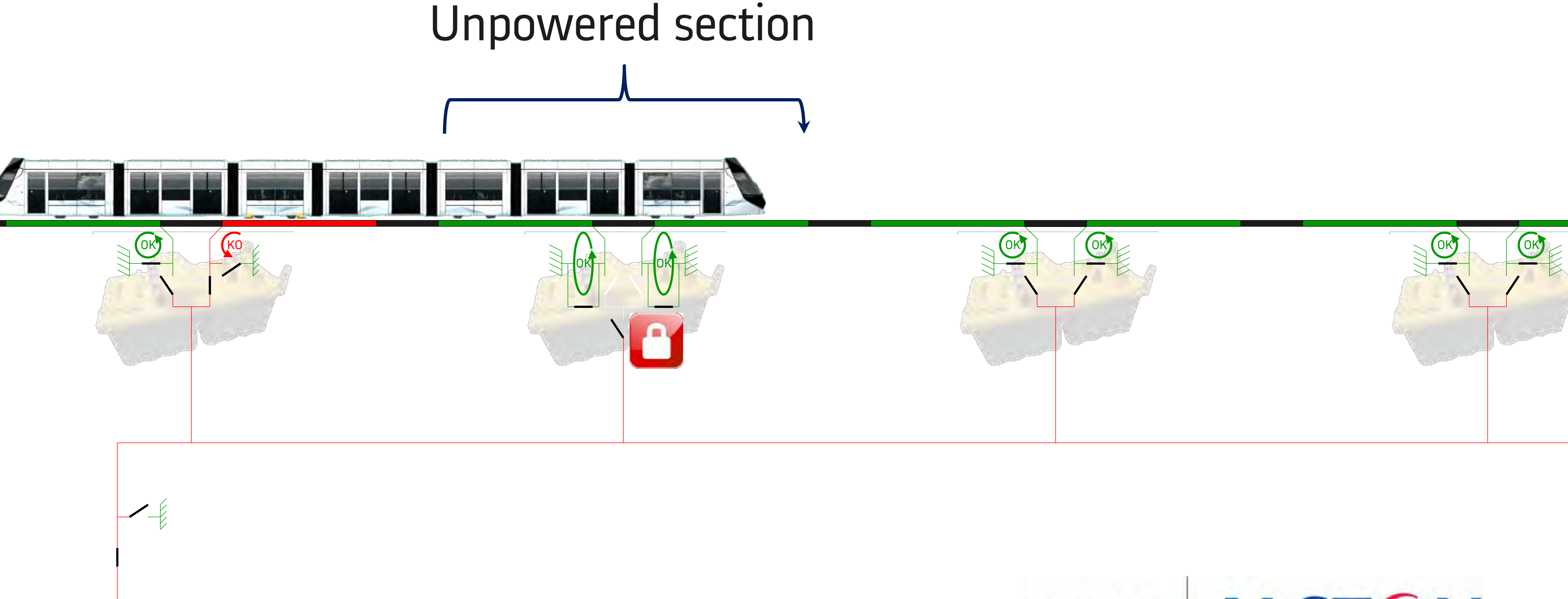
Next trams will run in autonomy mode on this isolated Power Box until replacement of the power box.



TRANSPORT ALSTOM

APS Basic Principle - Safety

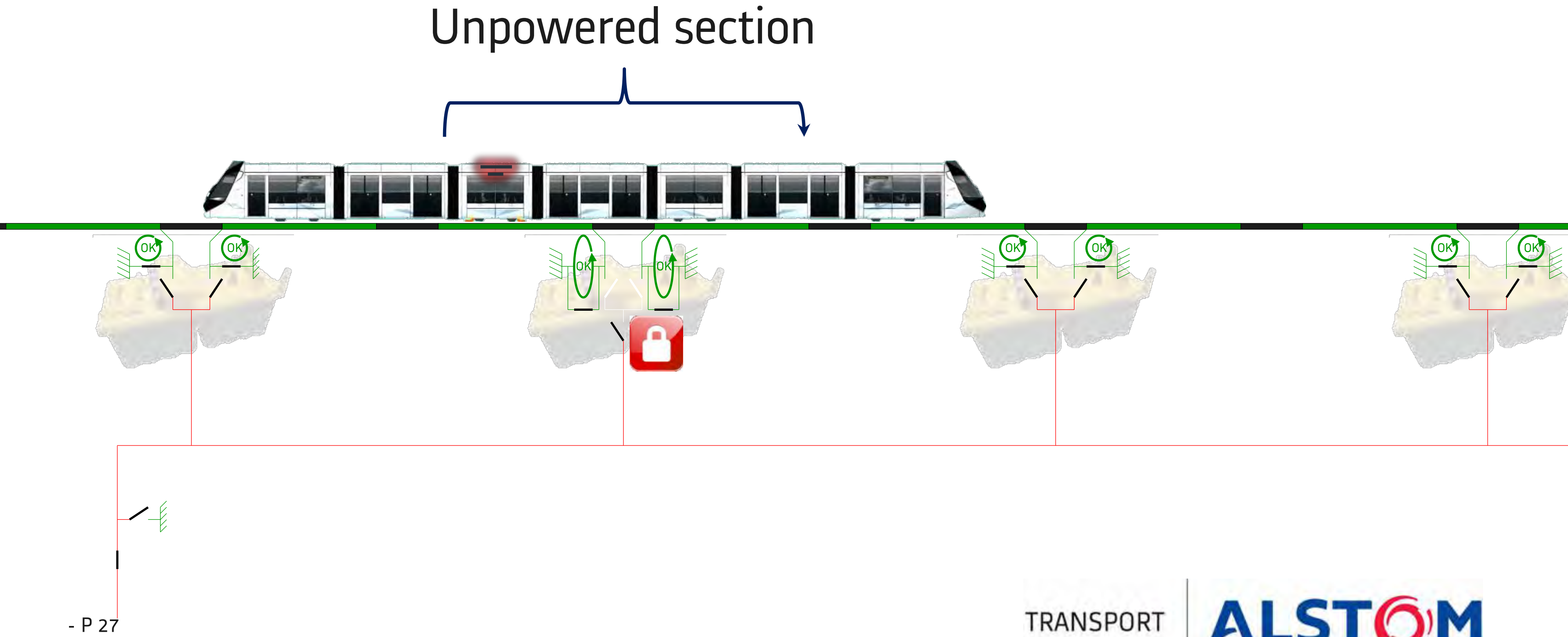
Next trams will run in autonomy mode on this isolated Power Box until replacement of the power box.



TRANSPORT ALSTOM

APS Basic Principle - Safety

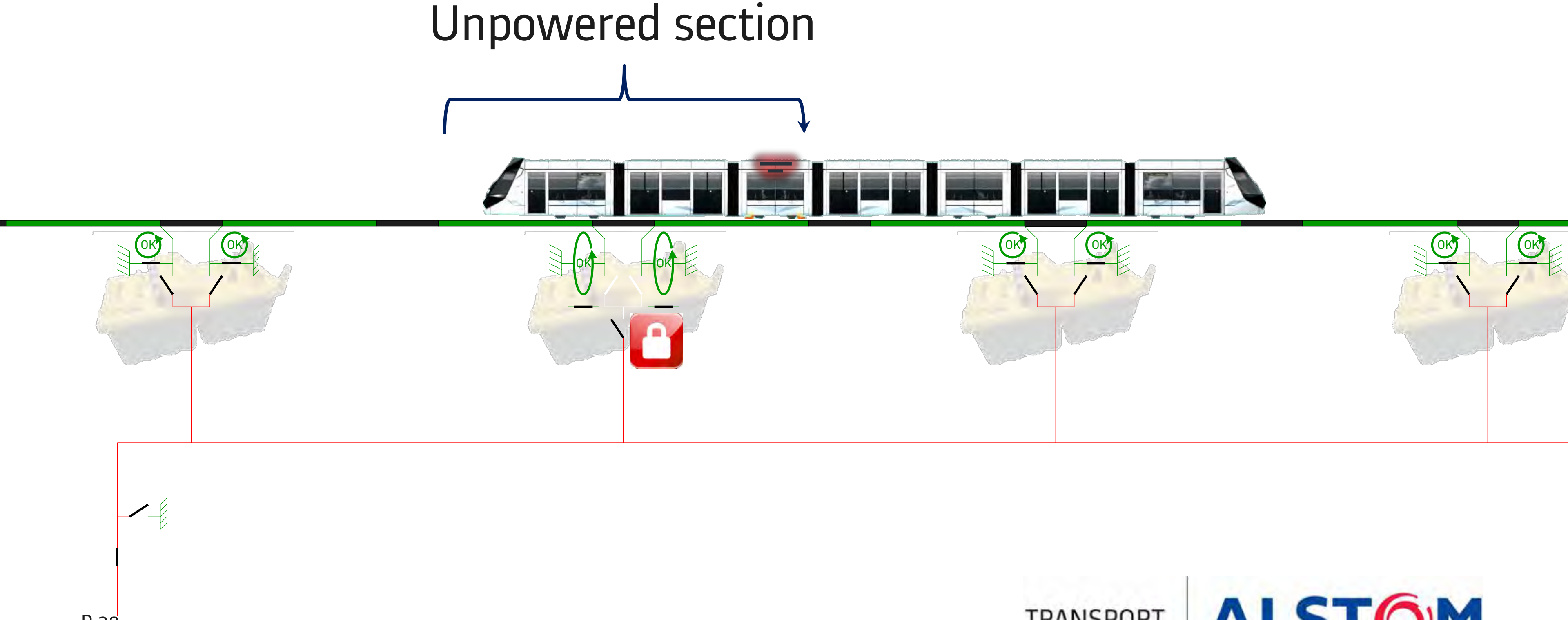
Next trams will run in autonomy mode on this isolated Power Box until replacement of the power box.



TRANSPORT ALSTOM

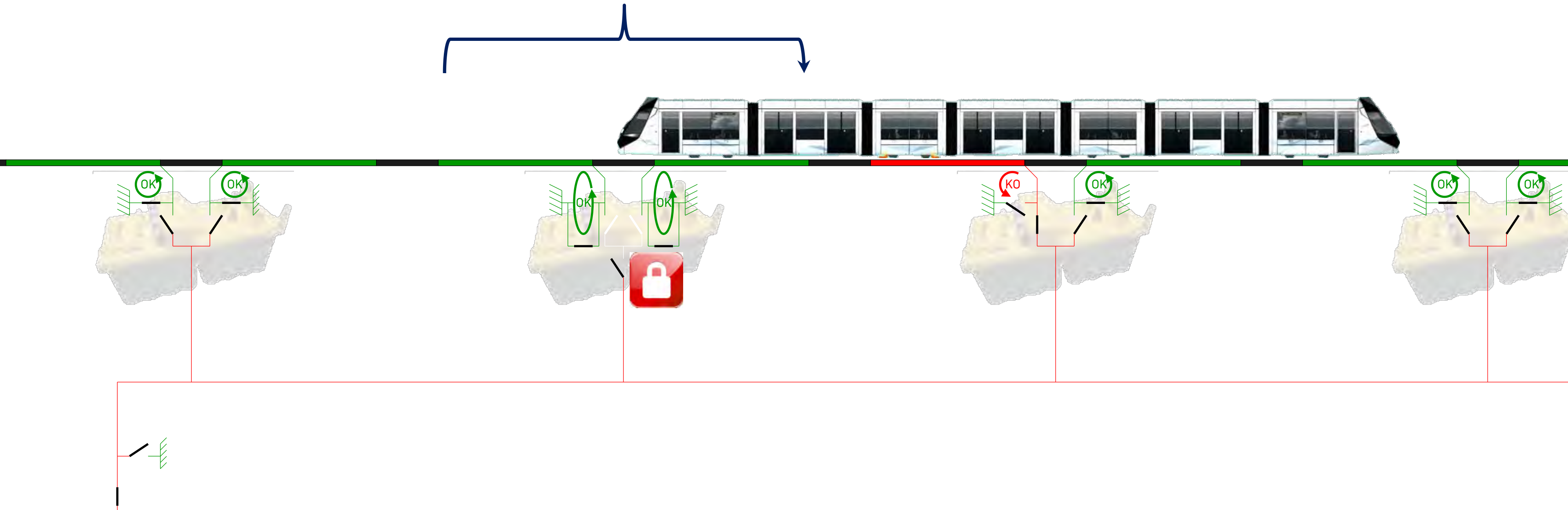
APS Basic Principle - Safety

Next trams will run in autonomy mode on this isolated Power Box until replacement of the power box.


Unpowered section

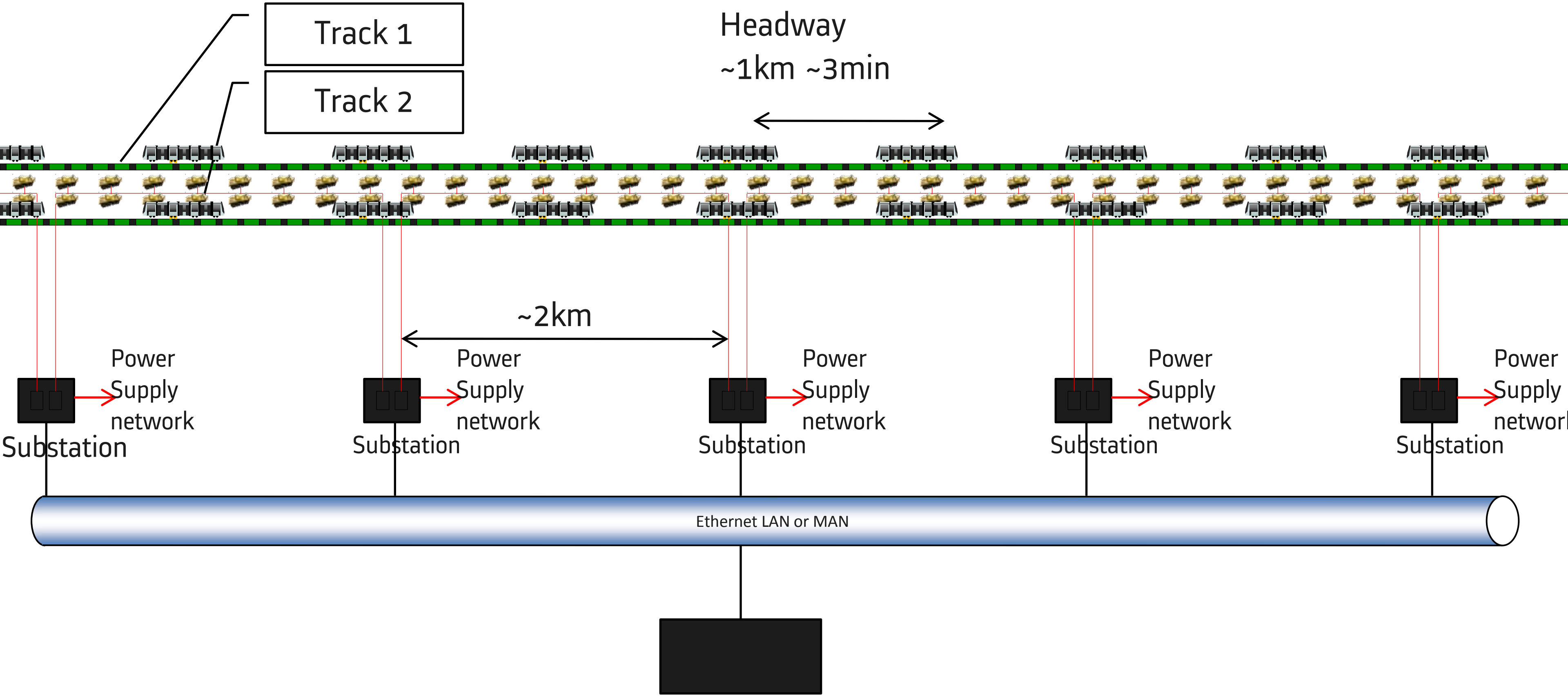
APS Basic Principle - Safety

Next trams will run in autonomy mode on this isolated Power Box until replacement of the power box.

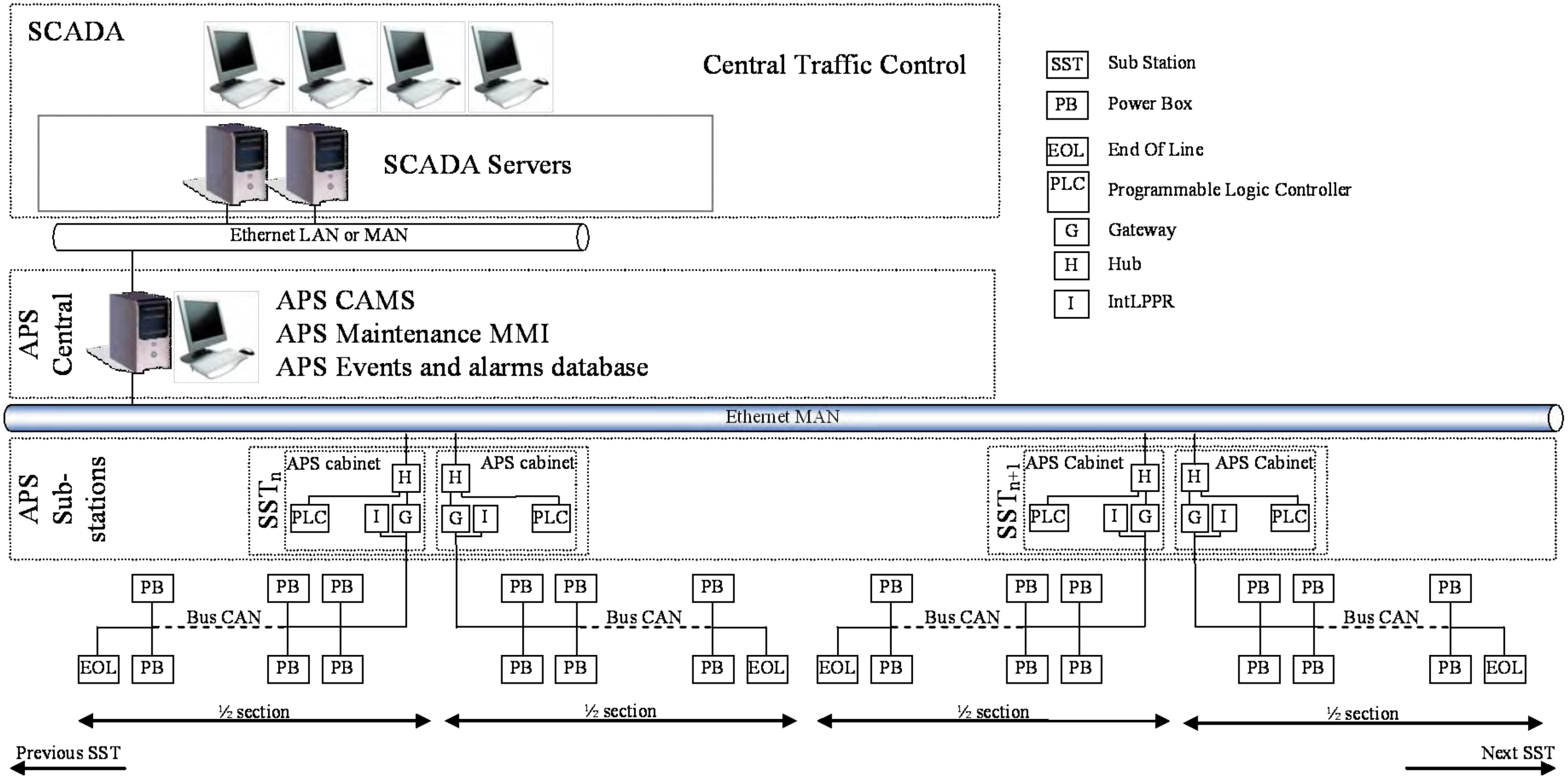


Unpowered section

APS Basic Principle - Overall architecture

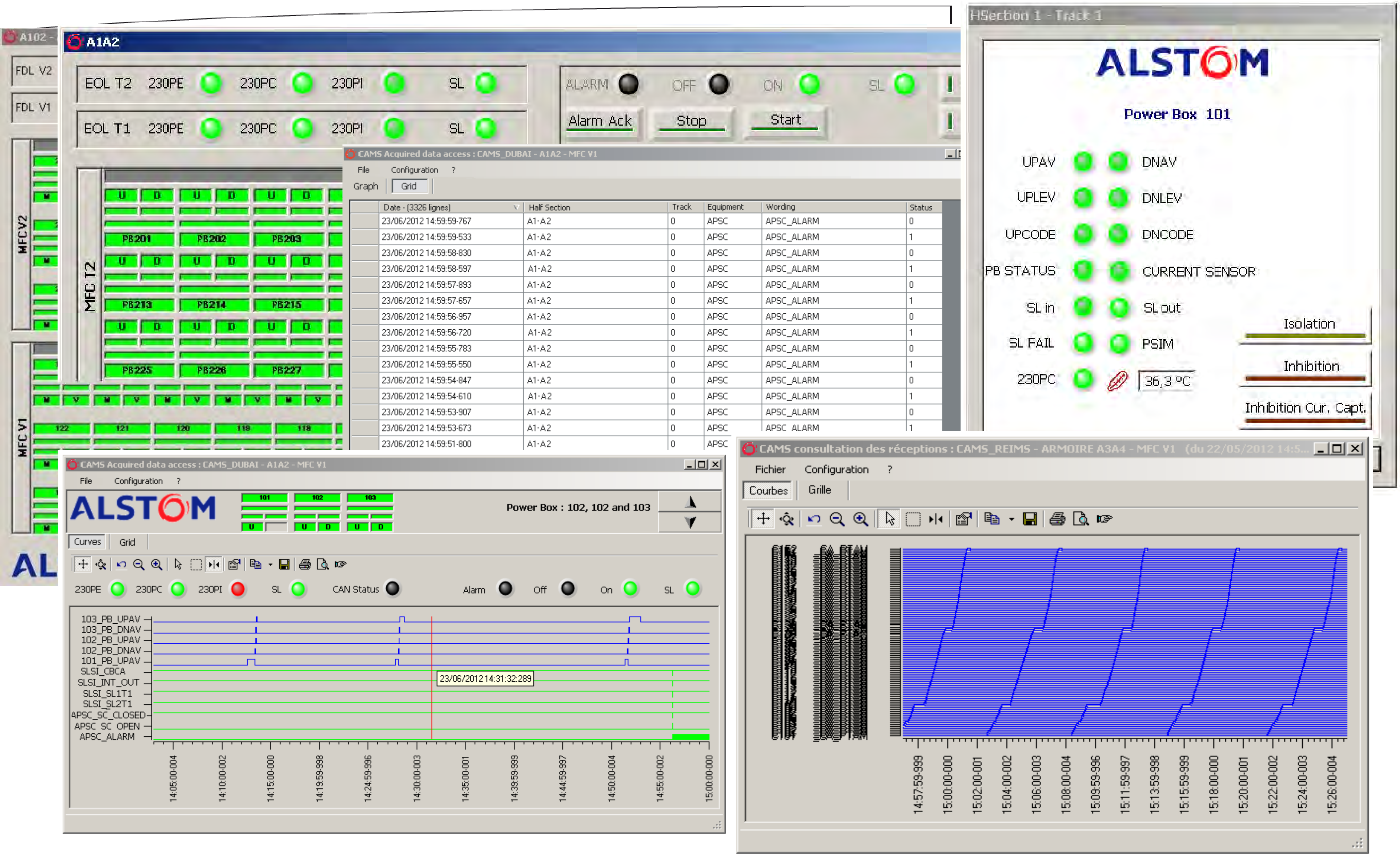


APS Basic Principle - Computerized Aided Maintenance System



SST	Sub Station
PB	Power Box
EOL	End Of Line
PLC	Programmable Logic Controller
G	Gateway
H	Hub
I	IntLPPR

Real time supervision
1ms dating accuracy for power box for diagnostic



CAMS Acquired data access : CAMS_DUBAI - A1A2 - MFC V1

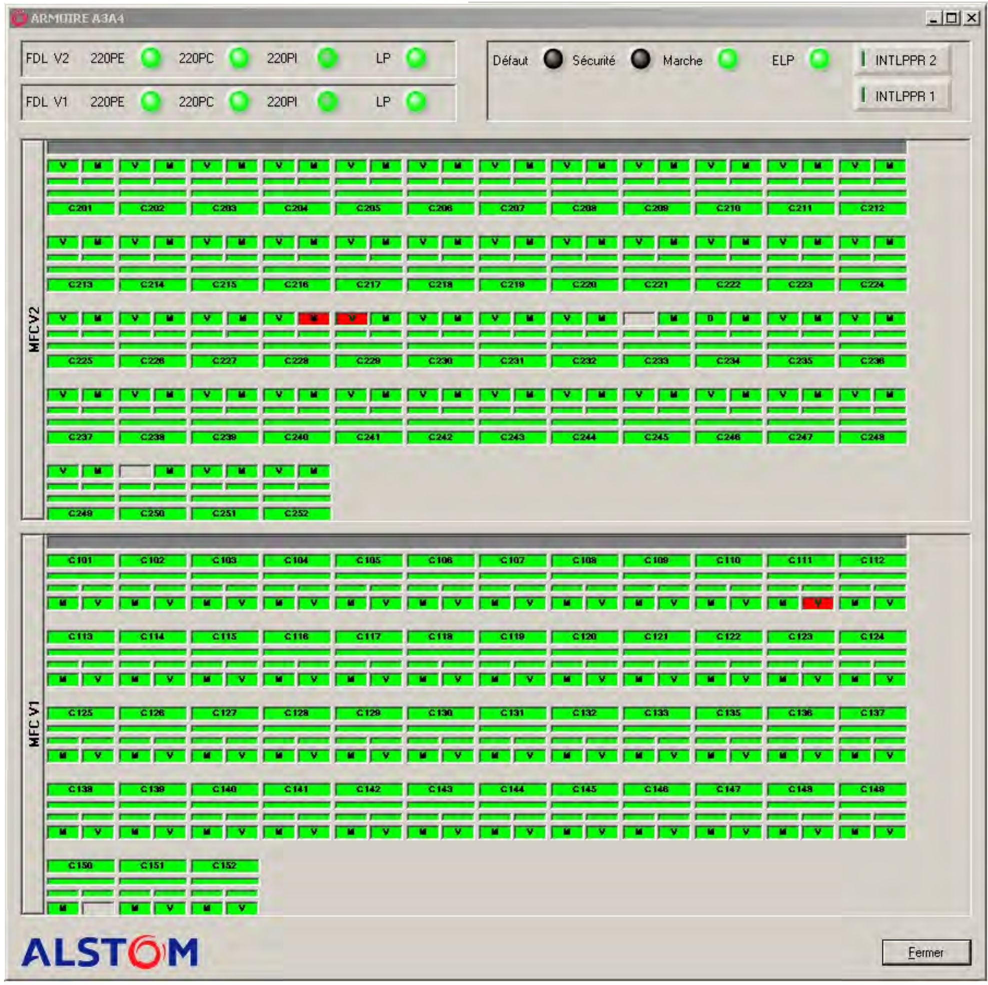
	Date - (3326 lignes)	Half Section	Track	Equipment	Wording	Status
	23/06/2012 14:59:59-767	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:59-533	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:58-830	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:58-597	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:57-893	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:57-657	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:56-957	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:56-720	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:55-783	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:55-550	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:54-847	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:54-610	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:53-907	A1-A2	0	APSC	APSC_ALARM	0
	23/06/2012 14:59:53-673	A1-A2	0	APSC	APSC_ALARM	1
	23/06/2012 14:59:51-800	A1-A2	0	APSC		

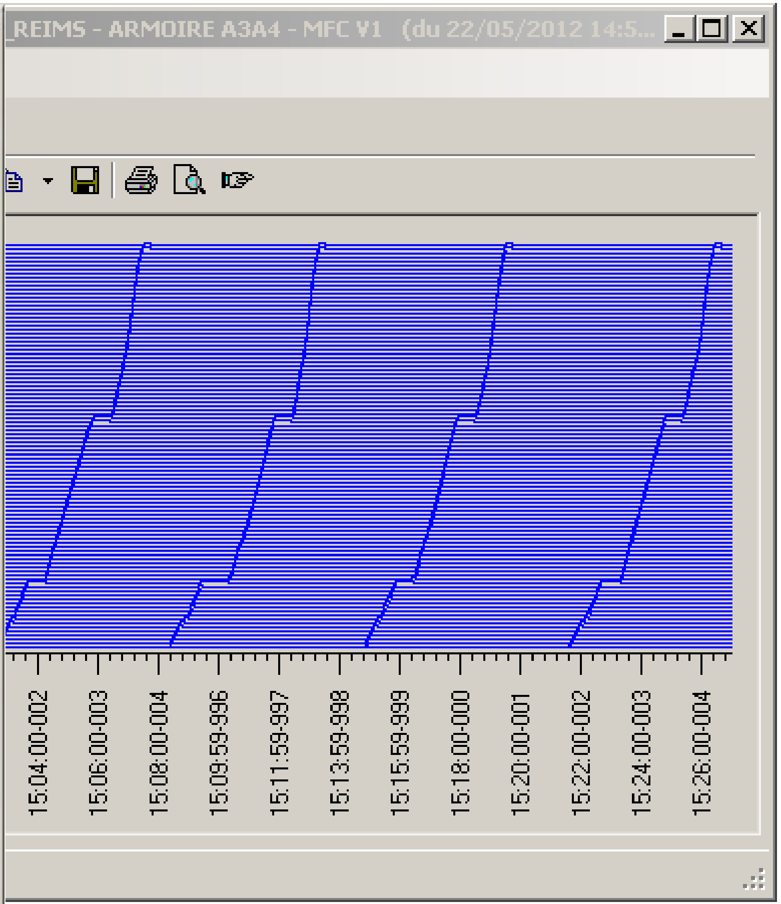
CAMS Acquired data access : CAMS_DUBAI - A1A2 - MFC V1

Power Box : 102, 102 and 103

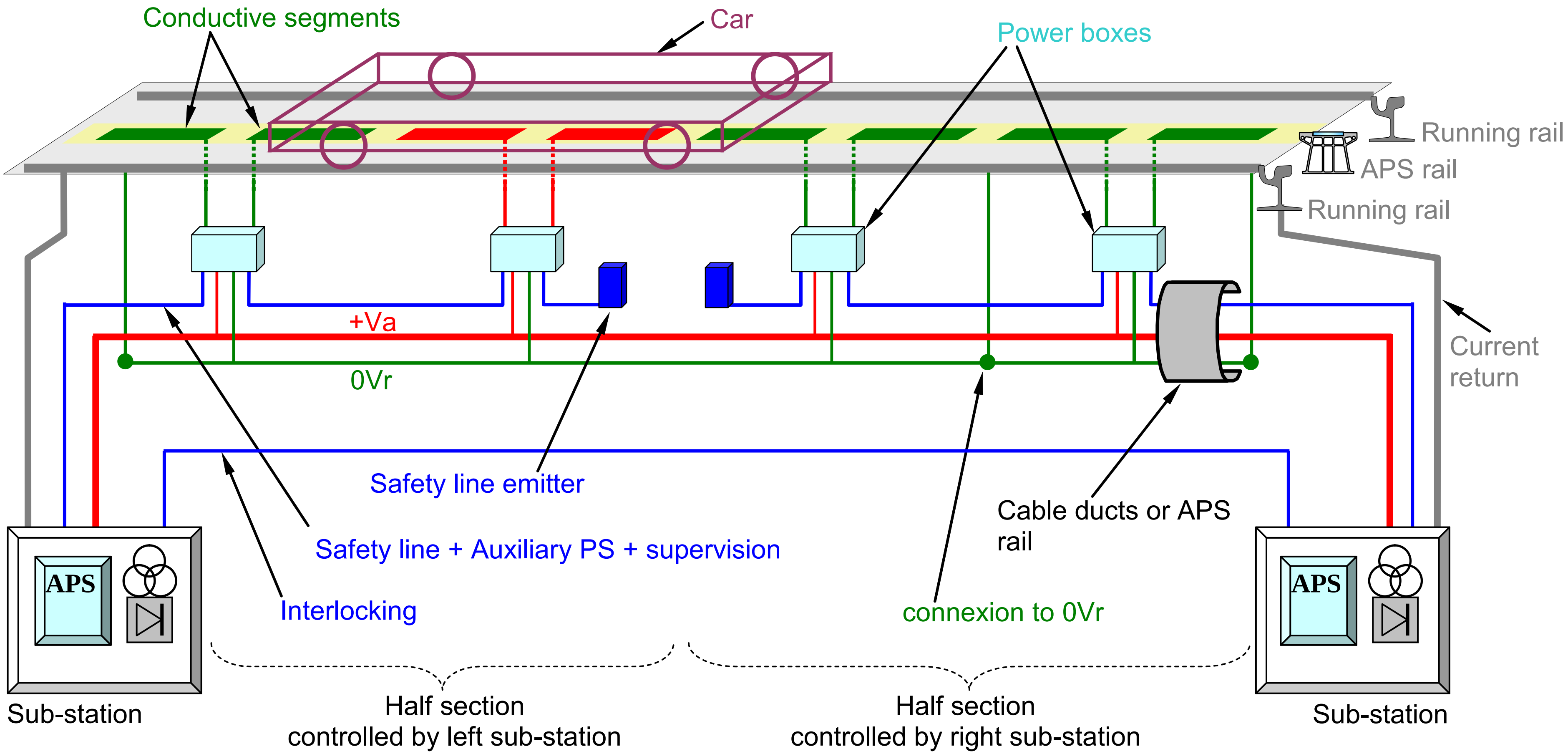
CAMS consultation des réceptions : CAMS_REIMS - ARMOIRE A3A4 - MFC V1 (du 22/05/2012 14:5...

CAMS animation

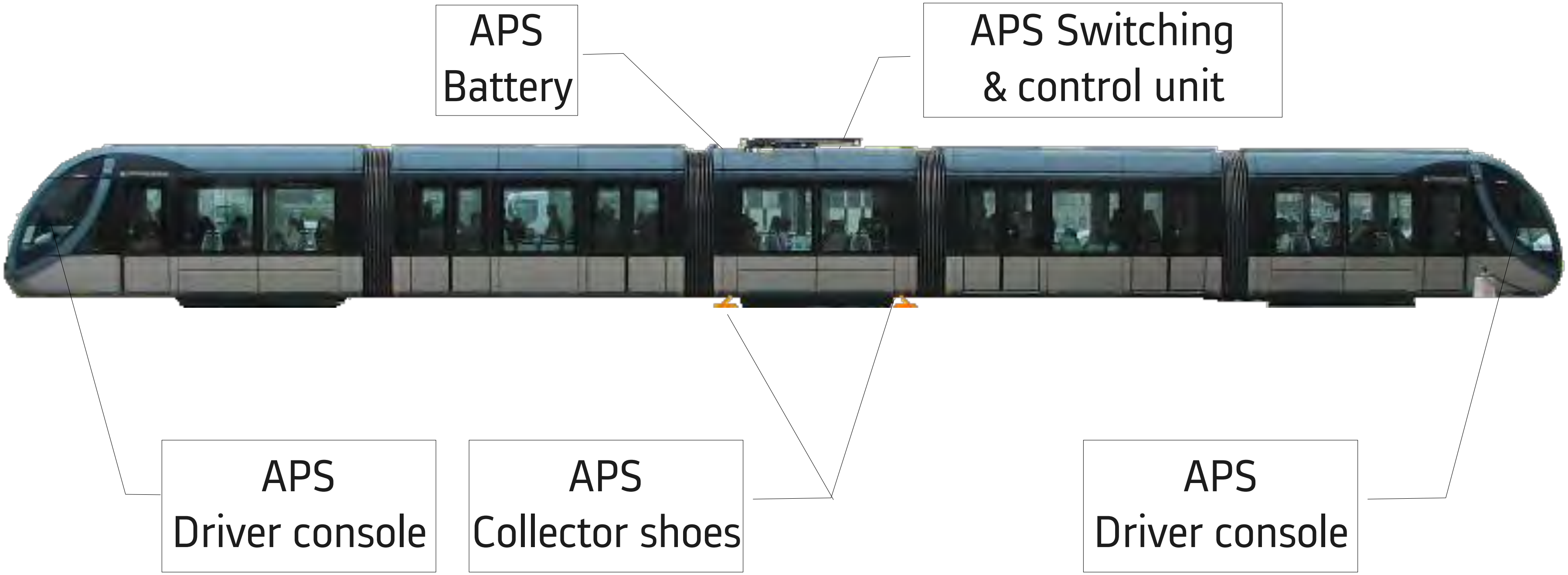




APS – Simplified architecture



APS system : Main Components on board



APS Battery

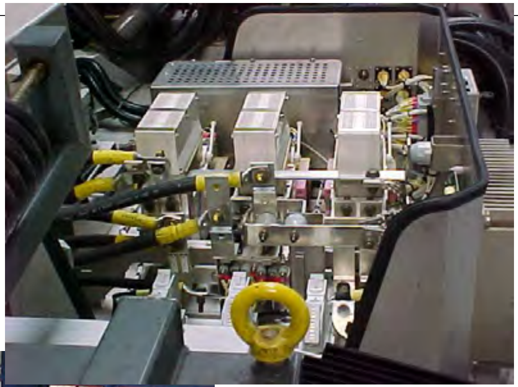
APS Switching & control unit

APS Driver console

APS Collector shoes

APS Driver console

APS system : Main Components on board

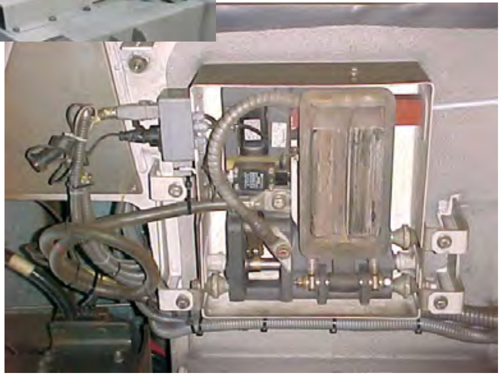


- This equipment allows switching the power source from APS to OCS or Battery

It includes the APS safety emettor

- Contingency APS battery to allow train motion in case of power box failure

It includes a battery charger 6 kVA and the battery (15 A.h)



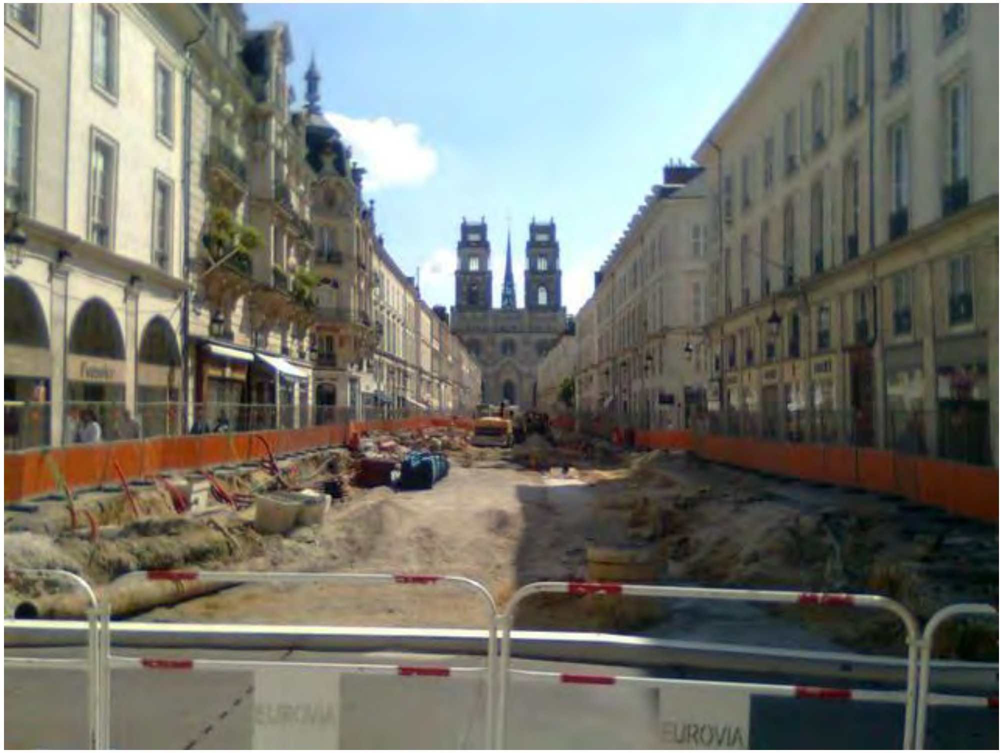
- Collector shoes in contact with the APS rail to take traction current from the 750 V Conductor rail

It includes the APS coded signal antenna

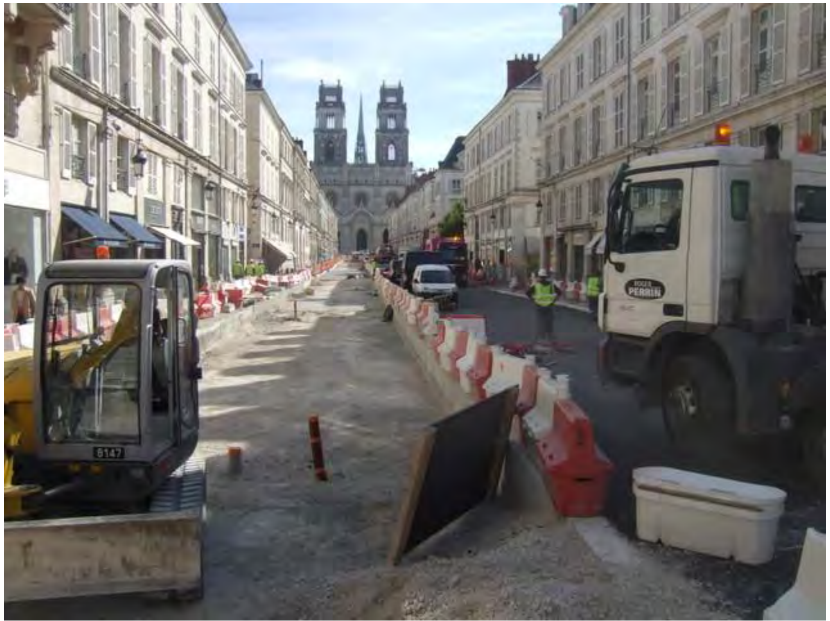
APS Installation process - Civil works – Plateform preparation

- Civil works preparation (levelling, networks redirection, drainage pipes installation…)

Networks redirection:

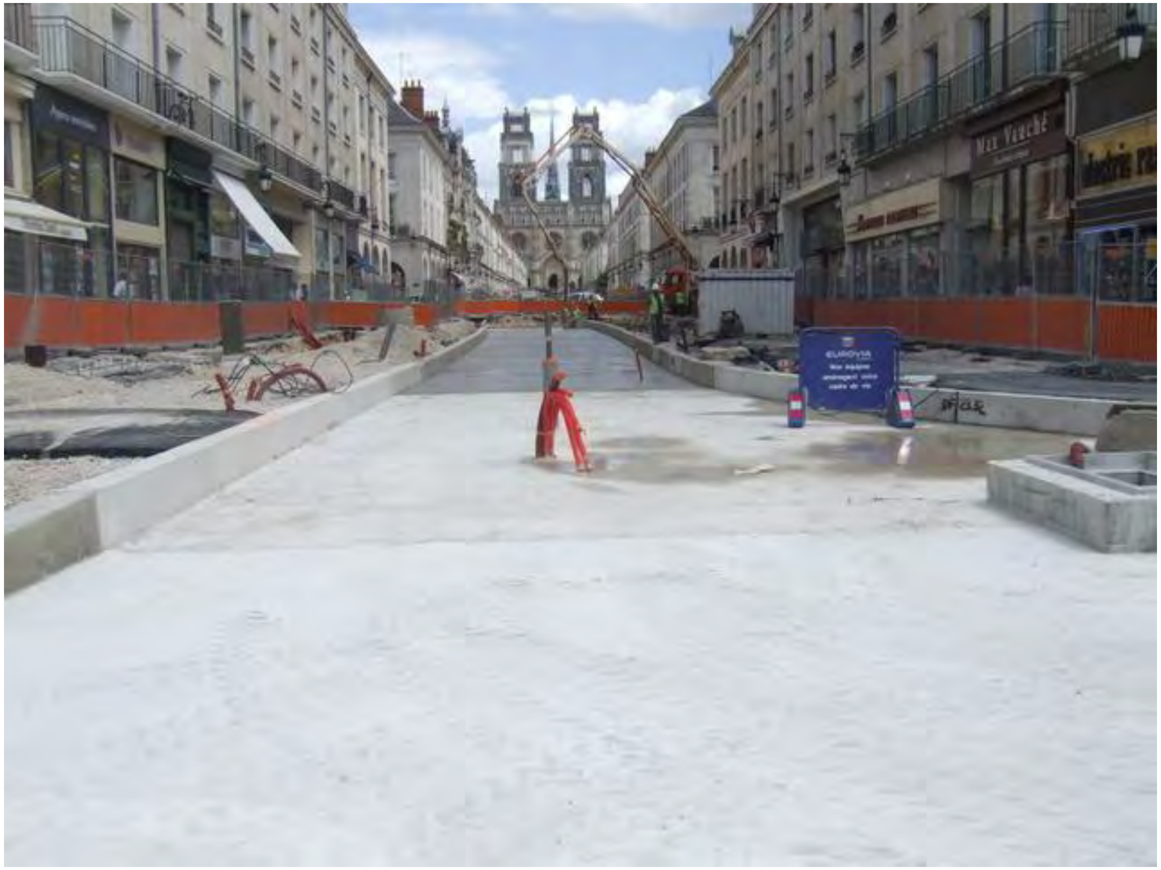


CW final works:



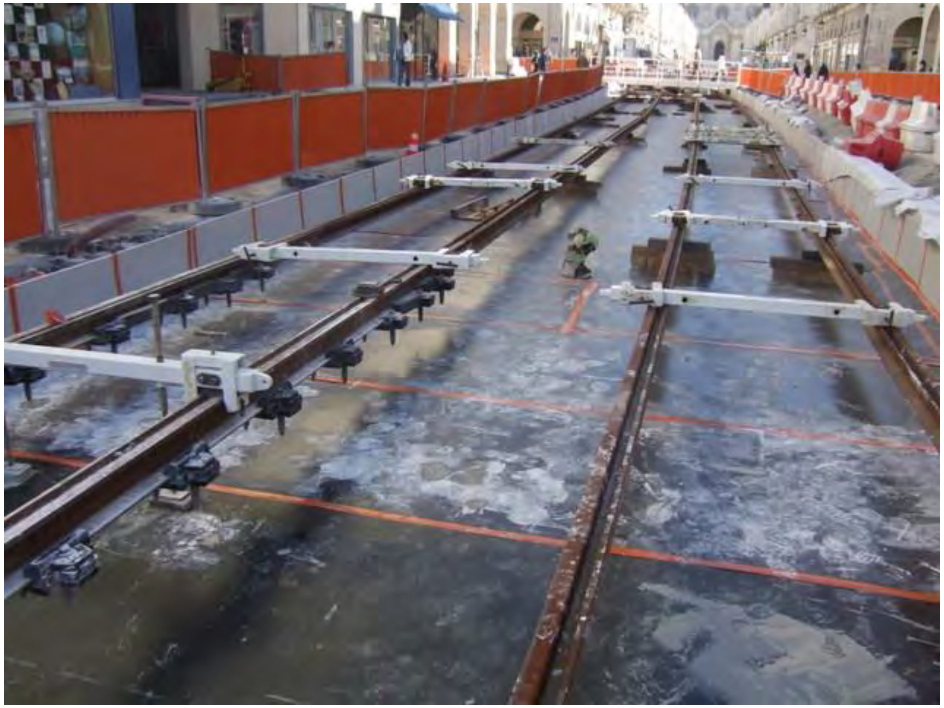
APS Installation process - Civil works – Fundation slab

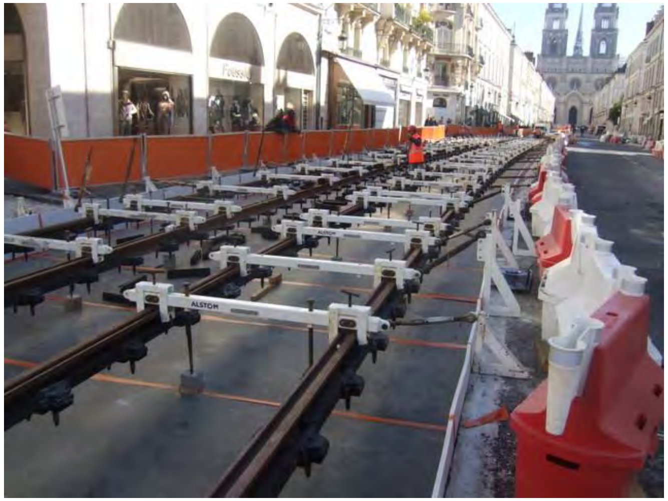
- Fundation slab pouring
- APS drainage pipes coming out of the slab are installed by CW



APS Installation process - Track – Rail positionning

- Track rails positionning with jigs

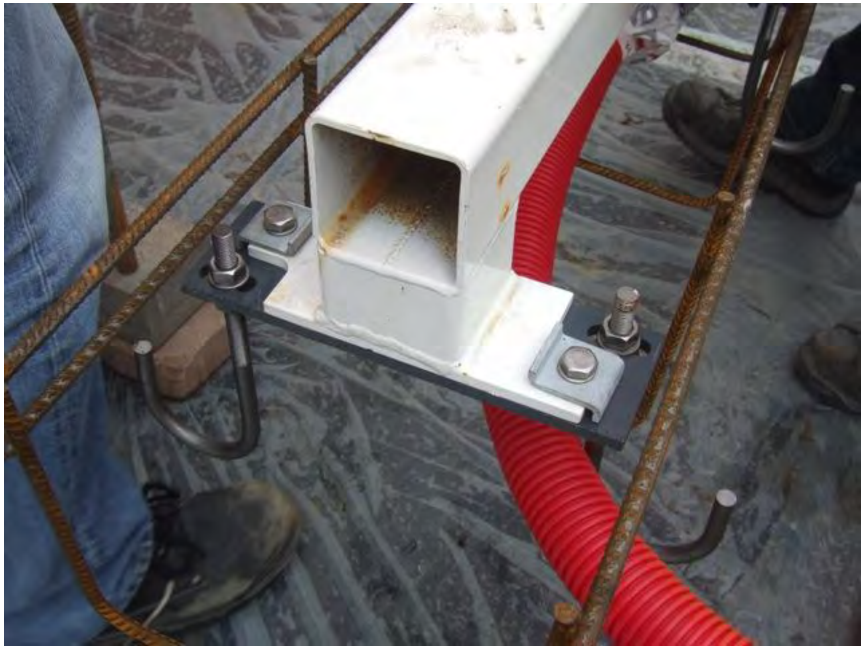


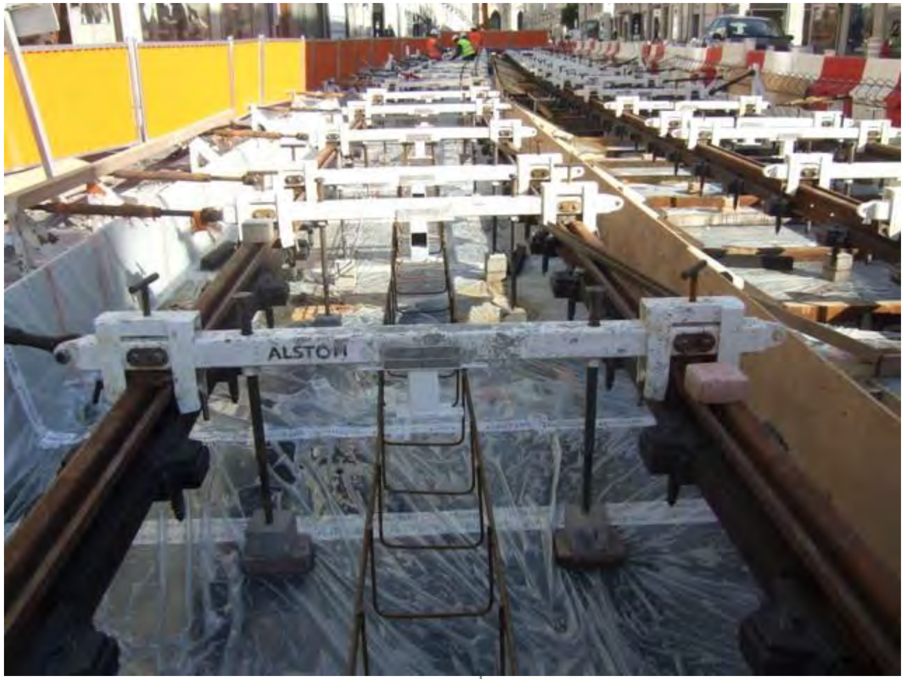


APS Installation process - Track – APS baseplates and re-bars

- Trackwork jigs are also used to hold APS baseplates and mesh for APS concrete

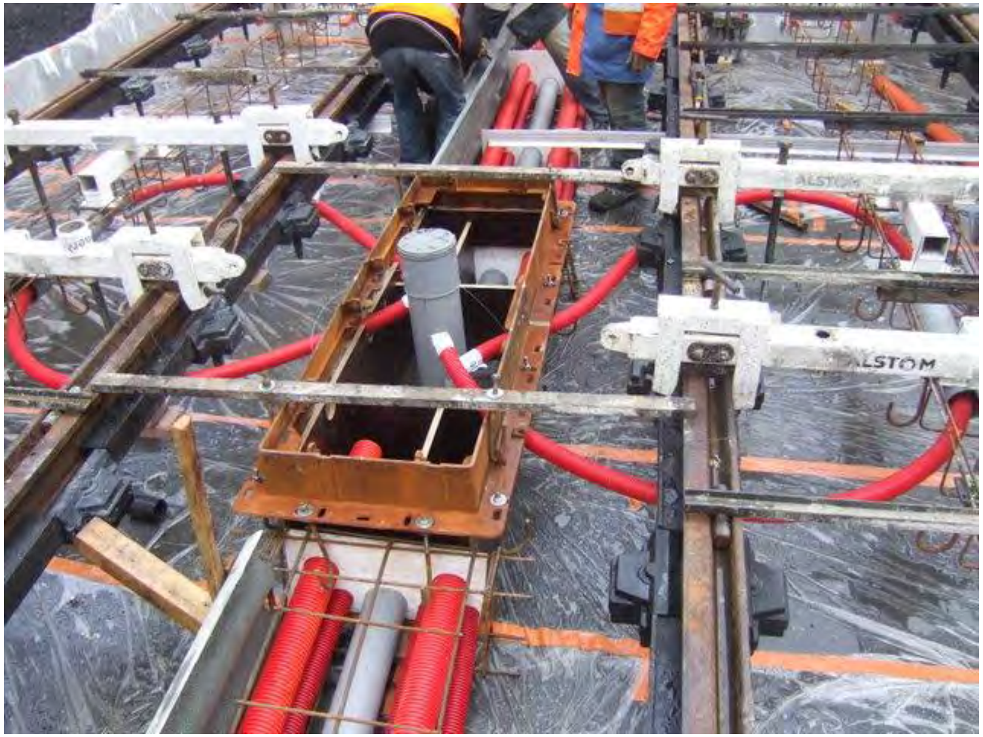
=> Jigs must be positionned by Track team according to APS calepinage

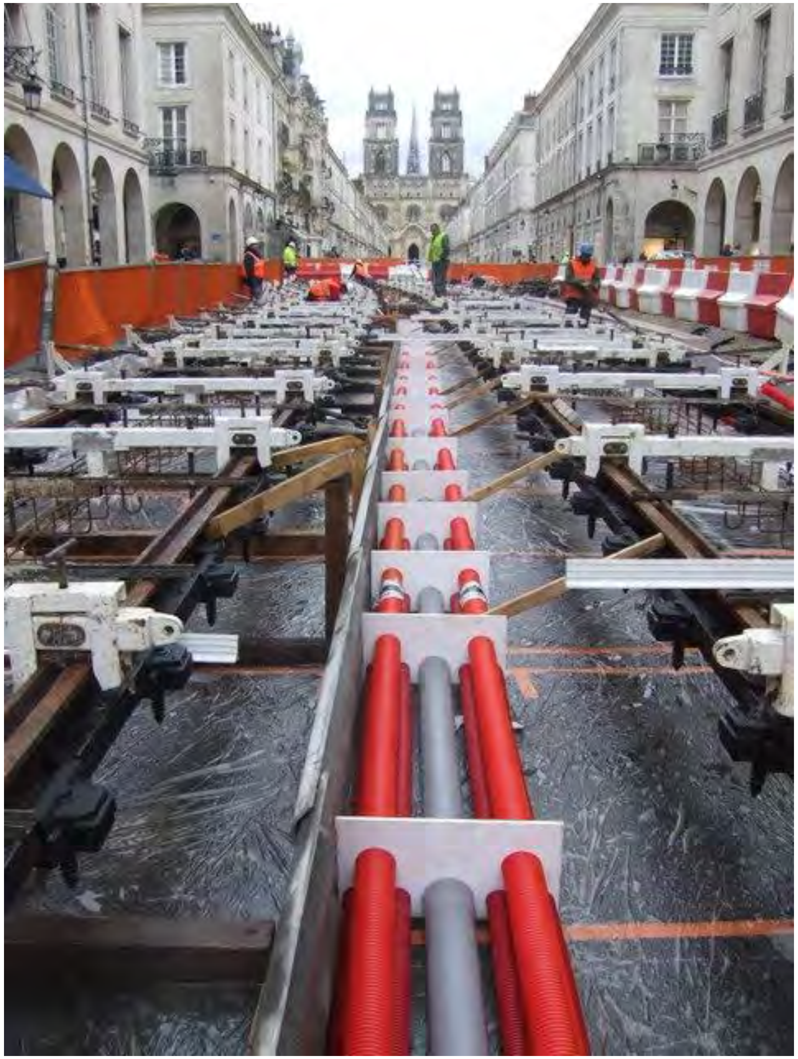




APS Installation process - Track – APS multitubular and chambers

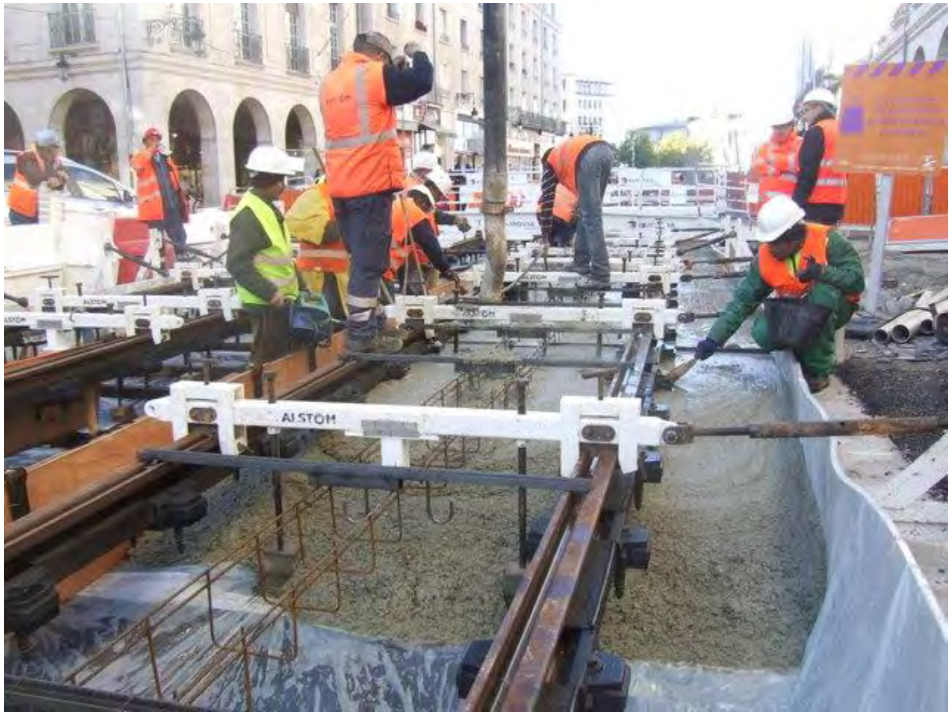
- Track teams install:
  - APS multitubular
  - APS power boxes chambers

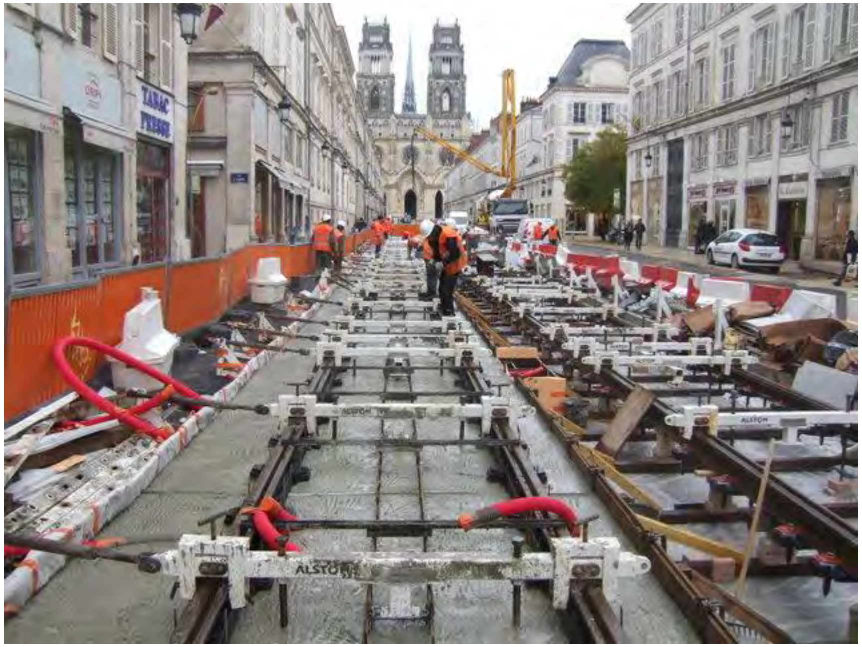




APS Installation process – Track slab

- Track slab pouring
- This slab holds APS baseplates and mesh



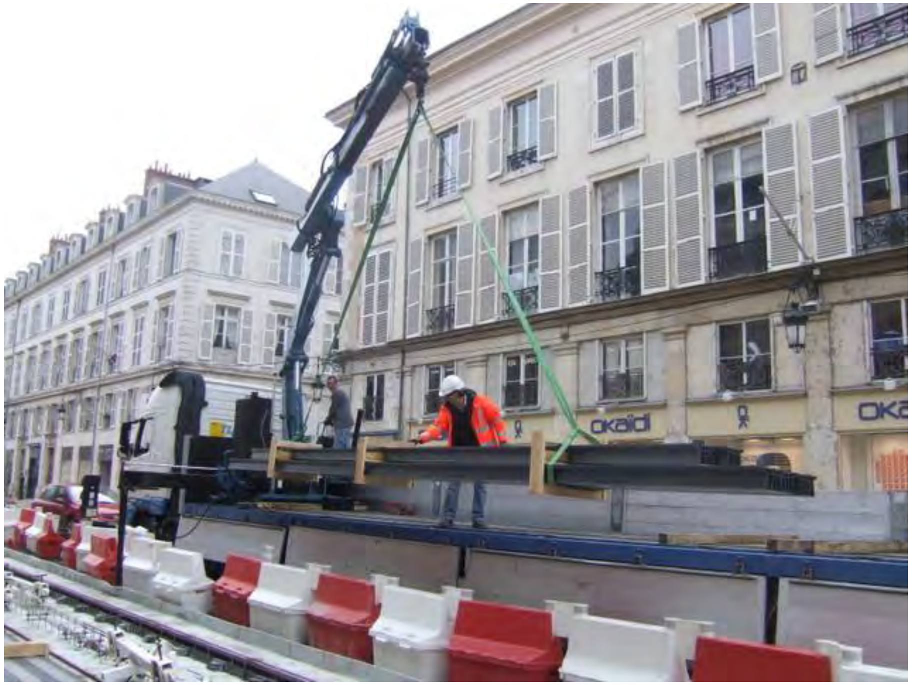


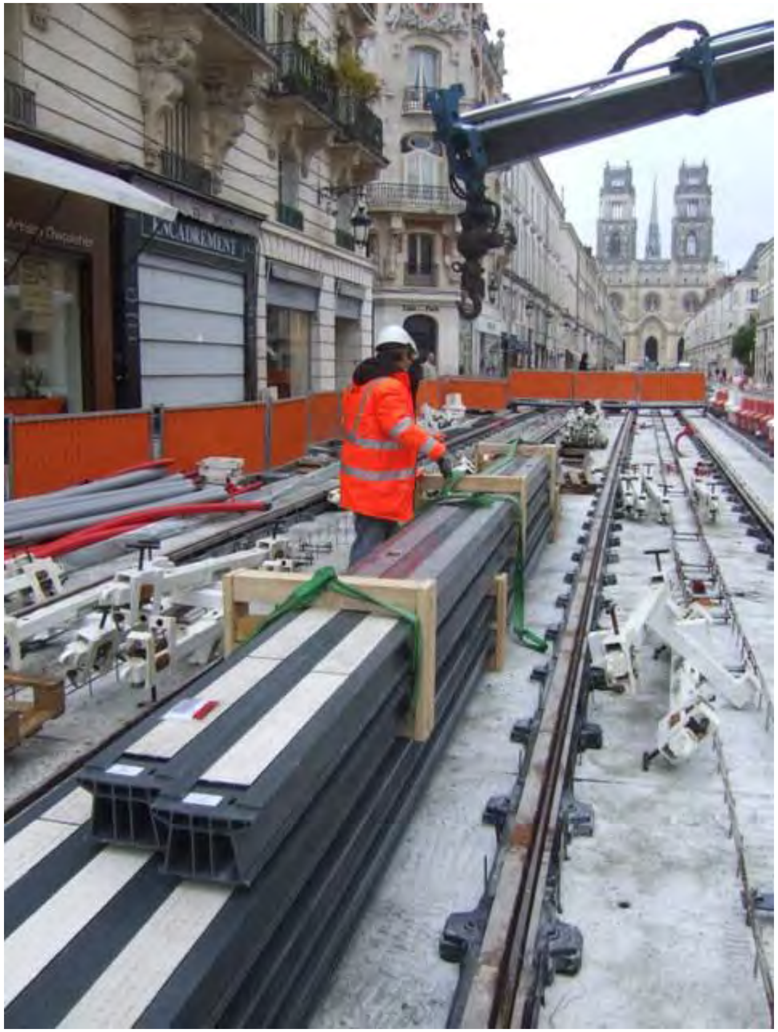
APS Installation process – transfer Track to APS

- APS controls Track works (equipments locations, number, condition…)

APS Installation process

- APS rails delivery



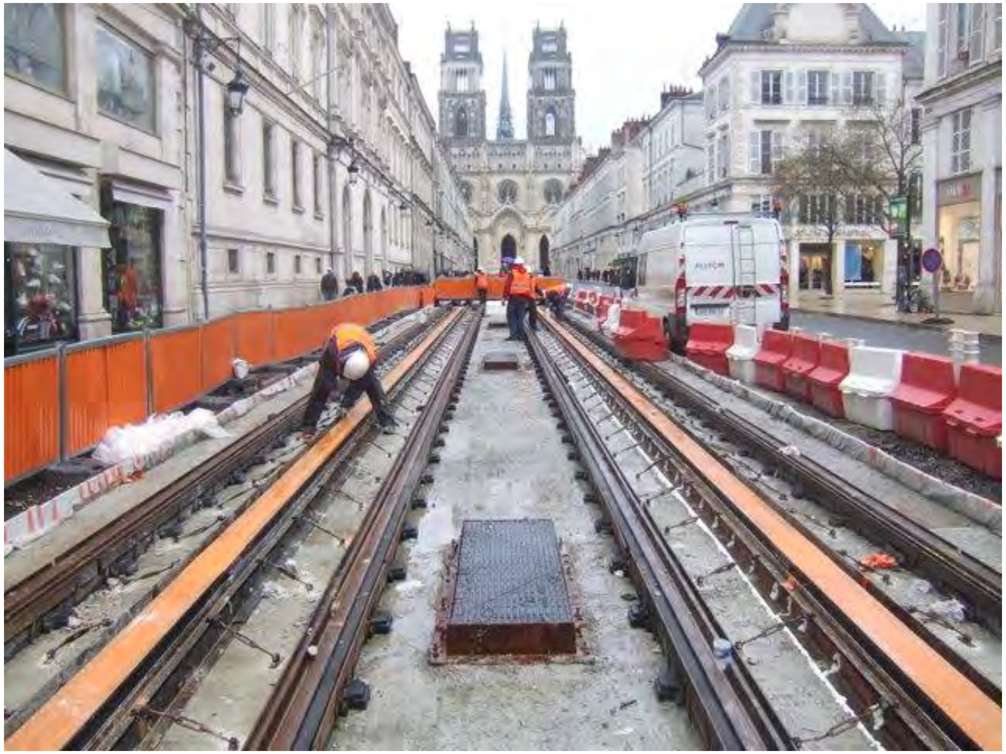


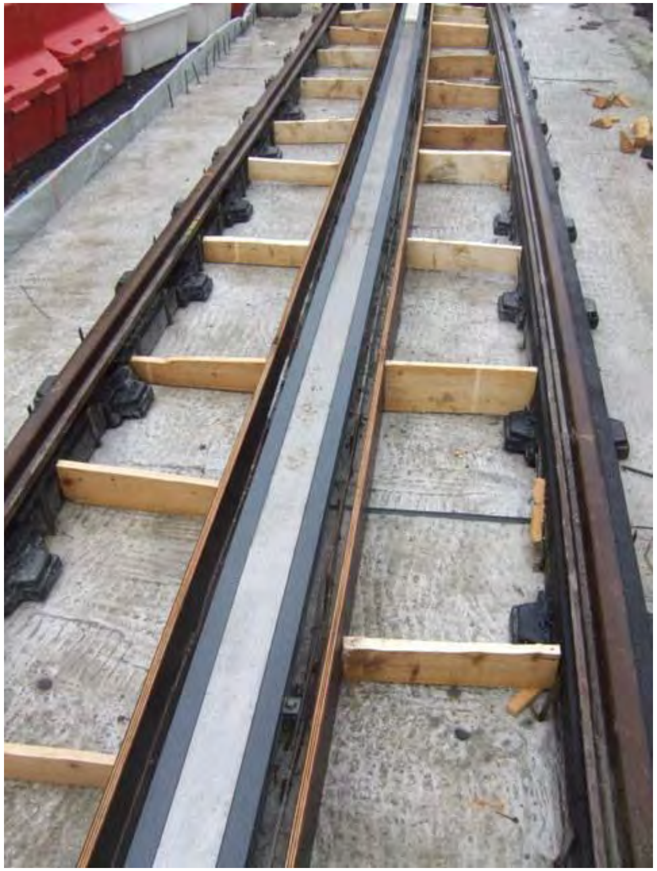
APS Installation process

- APS rail adjustment and control
- APS rail lies on baseplates positionned by Track teams
- APS rails location is controlled by APS quality team (millimetric precision):

APS Installation process

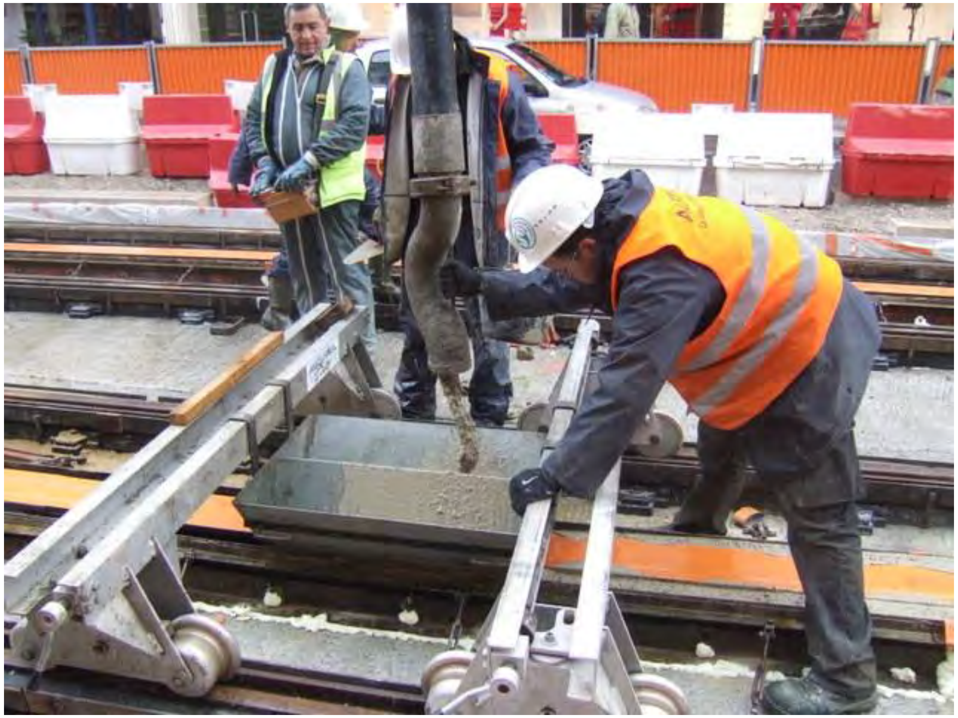
- APS formwork installation:
  - With metallic formwork in straight lines ;
  - With wooden formwork in cuves.





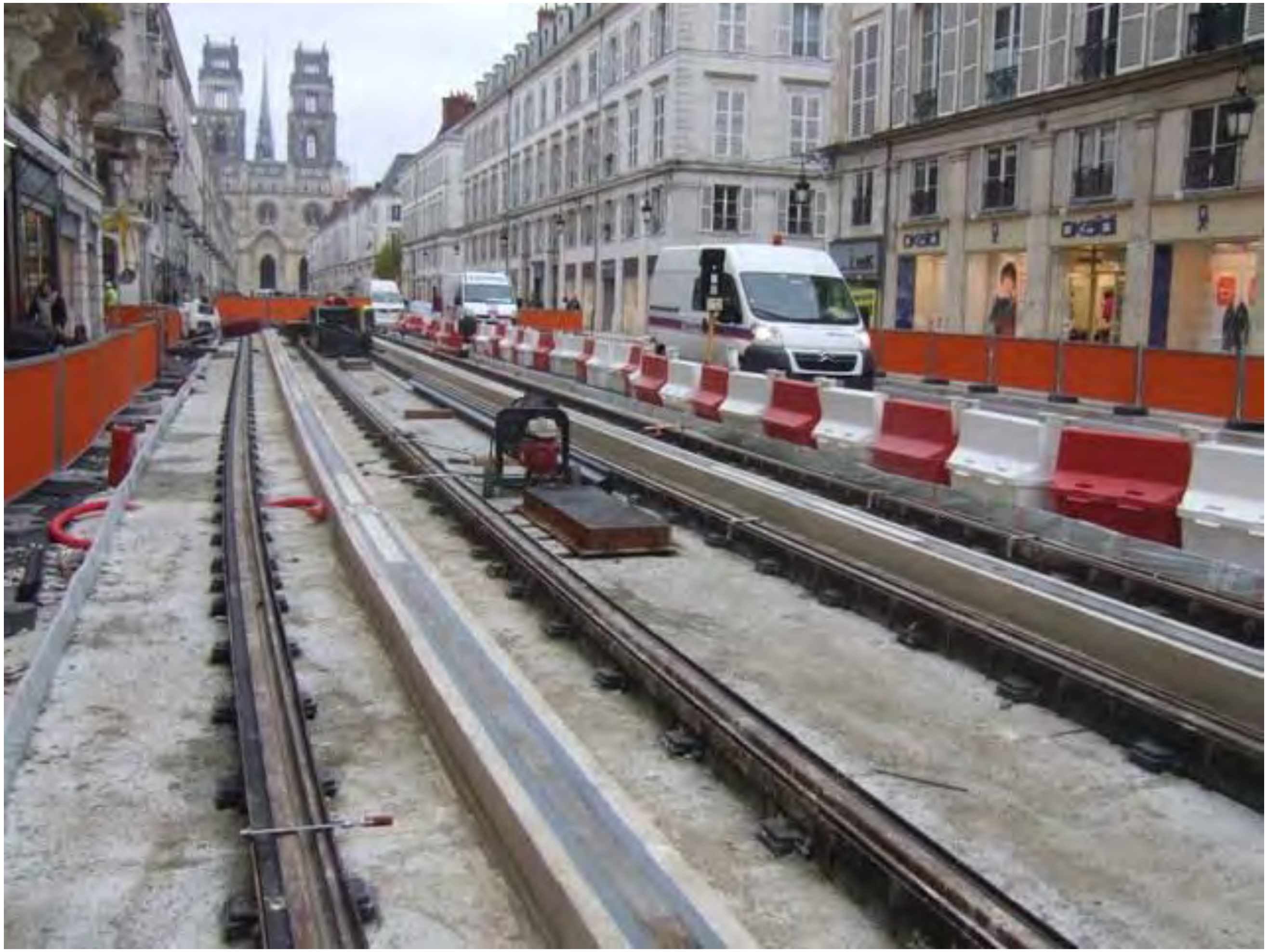
APS Installation process

- APS concrete pouring



APS Installation process

- Plateform after Track and APS works:



APS Installation process

- Final design after paving

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ALSTOM'S CATENARYLESS SOLUTIONS

2013, March 8th

ALSTOM

AGENDA

1/

Customer's wishes

- Which expectations for ours customers ?

2/

Alstom's Service Proven Catenaryless Solutions

- Which solutions have been demonstrated as service proven ?

3/

Coming Alstom's Catenaryless Solutions

- Which solutions are we proposing now and which middle term solutions are we working on ?

CUSTOMER'S WISHES

1/

Customer's wishes

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CUSTOMER’S WISHES

1.1

A portion of line requested as without Catenary

- To preserve the beauty of historical areas or city centers
- To deal with existing Civil works constrains (limited gauge under bridge for instance)
- To maintain the real estate value
- To ensure fire brigade intervention

1.2

Full Catenaryless solution (No Catenary at all)

- To preserve all the project from overhead contact wires and poles as well

ALSTOM’S SERVICE PROVEN SOLUTIONS

1/

Customer’s wishes

- Which expectations for ours customers ?

2/

Alstom’s Service Proven Catenaryless Solutions

- Which solutions have been demonstrated as service proven ?

3/

Coming Alstom’s Catenaryless Solutions

- Which solutions are we proposing now and which middle term solutions are we working on ?

ALSTOM'S SERVICE PROVEN SOLUTIONS

APS
Aesthetic Power Supply

- In operation from 2003 (Bordeaux), 4 cities equipped, 2 more in construction.

On Board Battery

- In operation since 2007 in Nice.

On Board Supercaps

- Experimentation in 2010 in commercial service with French RATP Authority.

ALSTOM'S SERVICE PROVEN SOLUTIONS

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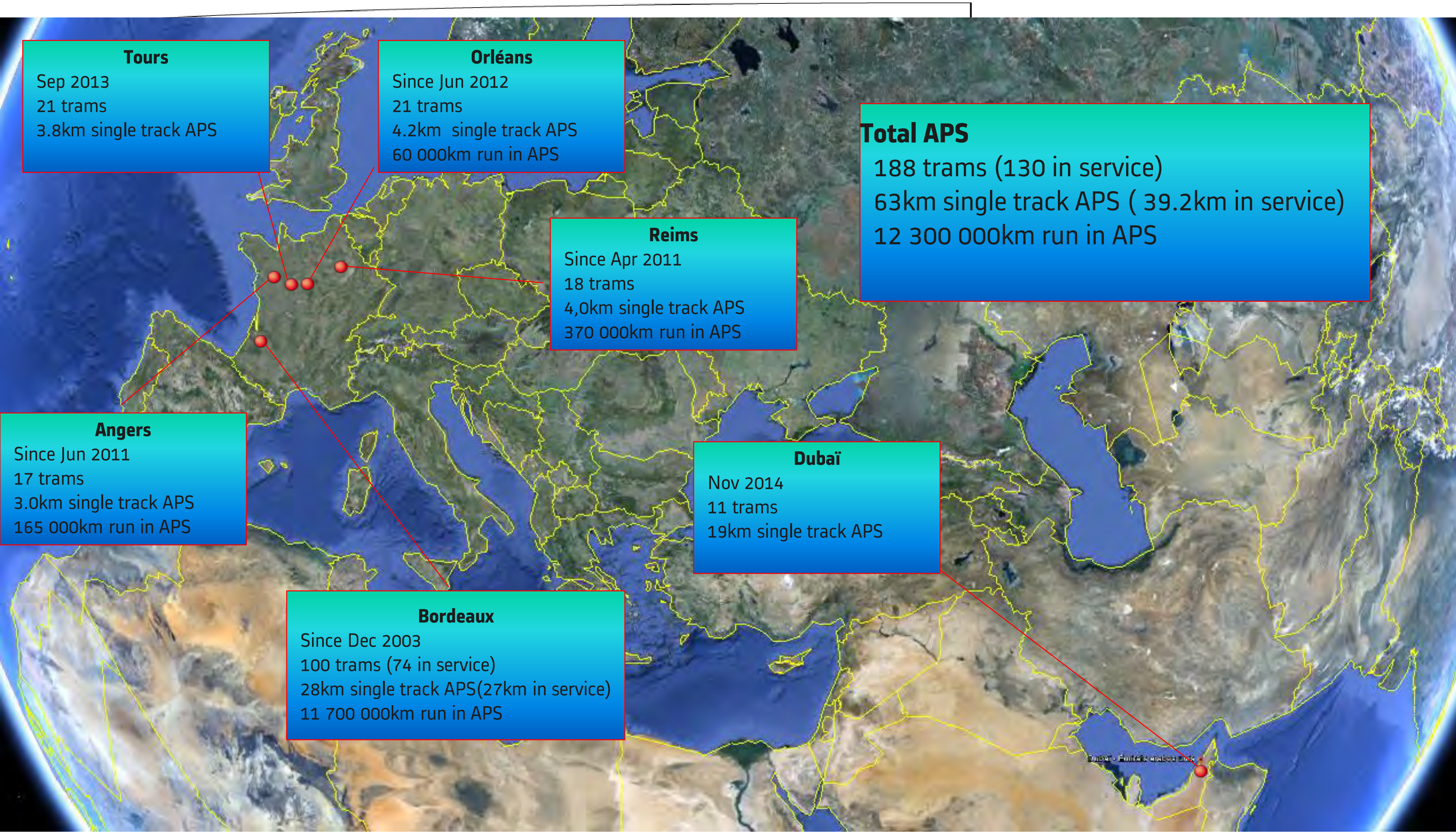
AESTHETIC POWER SUPPLY – APS

AESTHETIC POWER SUPPLY – APS - Projects location



Tours
Sep 2013
21 trams
3.8km single track APS

Orléans
Since Jun 2012
21 trams
4.2km single track APS
60 000km run in APS

Total APS
188 trams (130 in service)
63km single track APS (39.2km in service)
12 300 000km run in APS

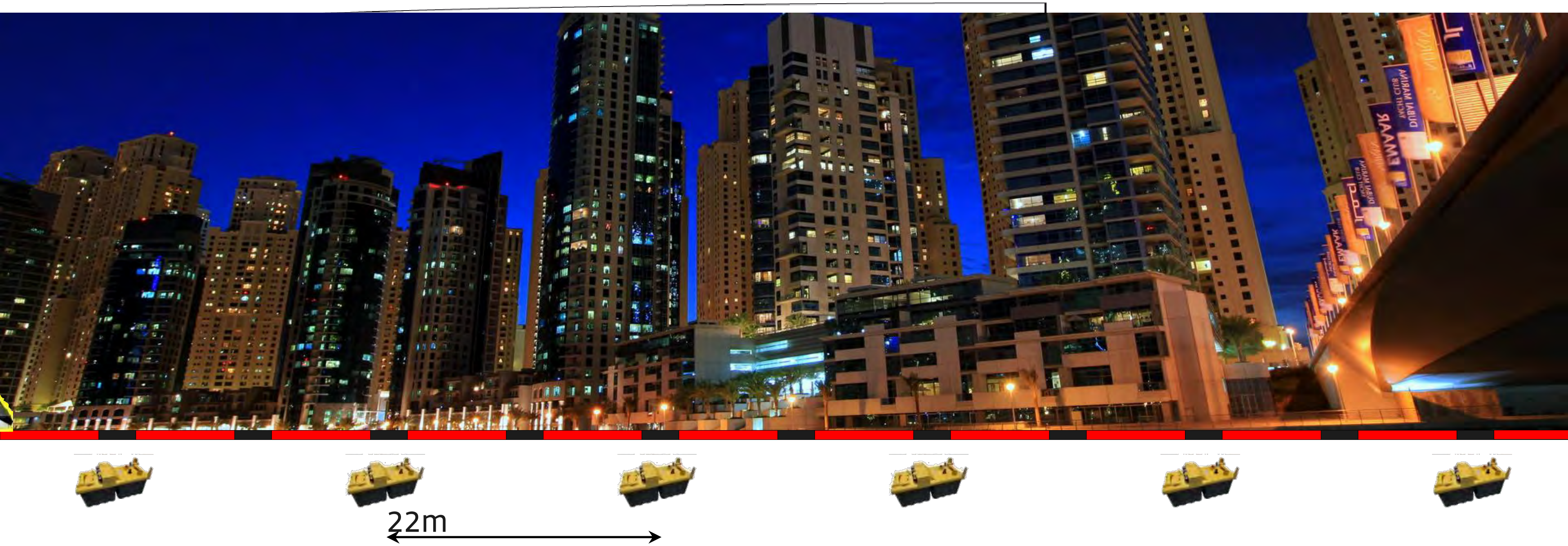
Reims
Since Apr 2011
18 trams
4,0km single track APS
370 000km run in APS

Angers
Since Jun 2011
17 trams
3.0km single track APS
165 000km run in APS

Dubaï
Nov 2014
11 trams
19km single track APS

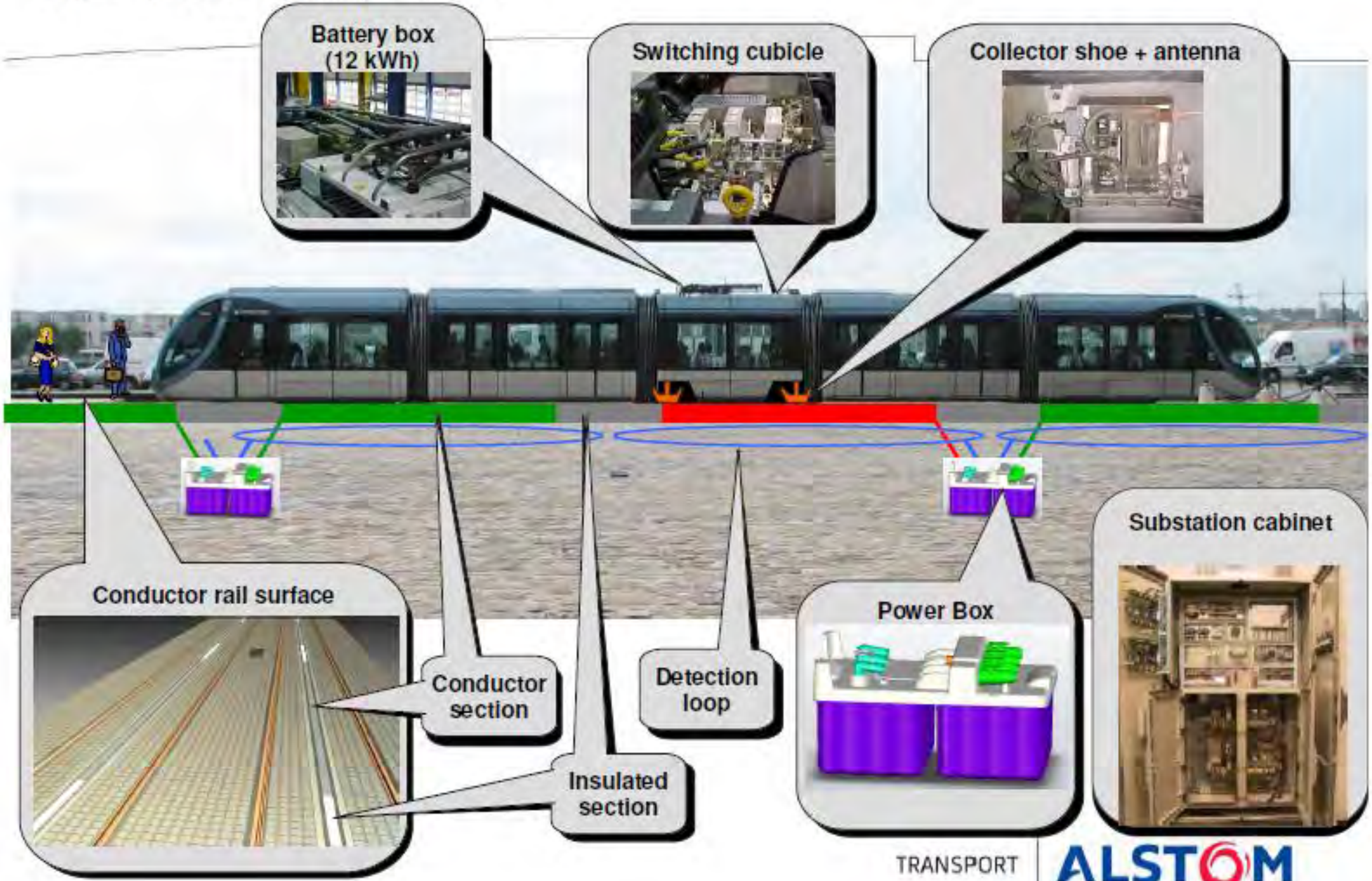
Bordeaux
Since Dec 2003
100 trams (74 in service)
28km single track APS(27km in service)
11 700 000km run in APS

APS Basic Principle



- ✓ Period : 11m / Conductive Segment 8m / Neutral zone : 3m
- ✓ Each power box drives 2 segments, a power box every 22m
- ✓ Tramways are 30 or 40m long, covering every live segments
- ✓ After tram passage, the segment is connected to the rail voltage

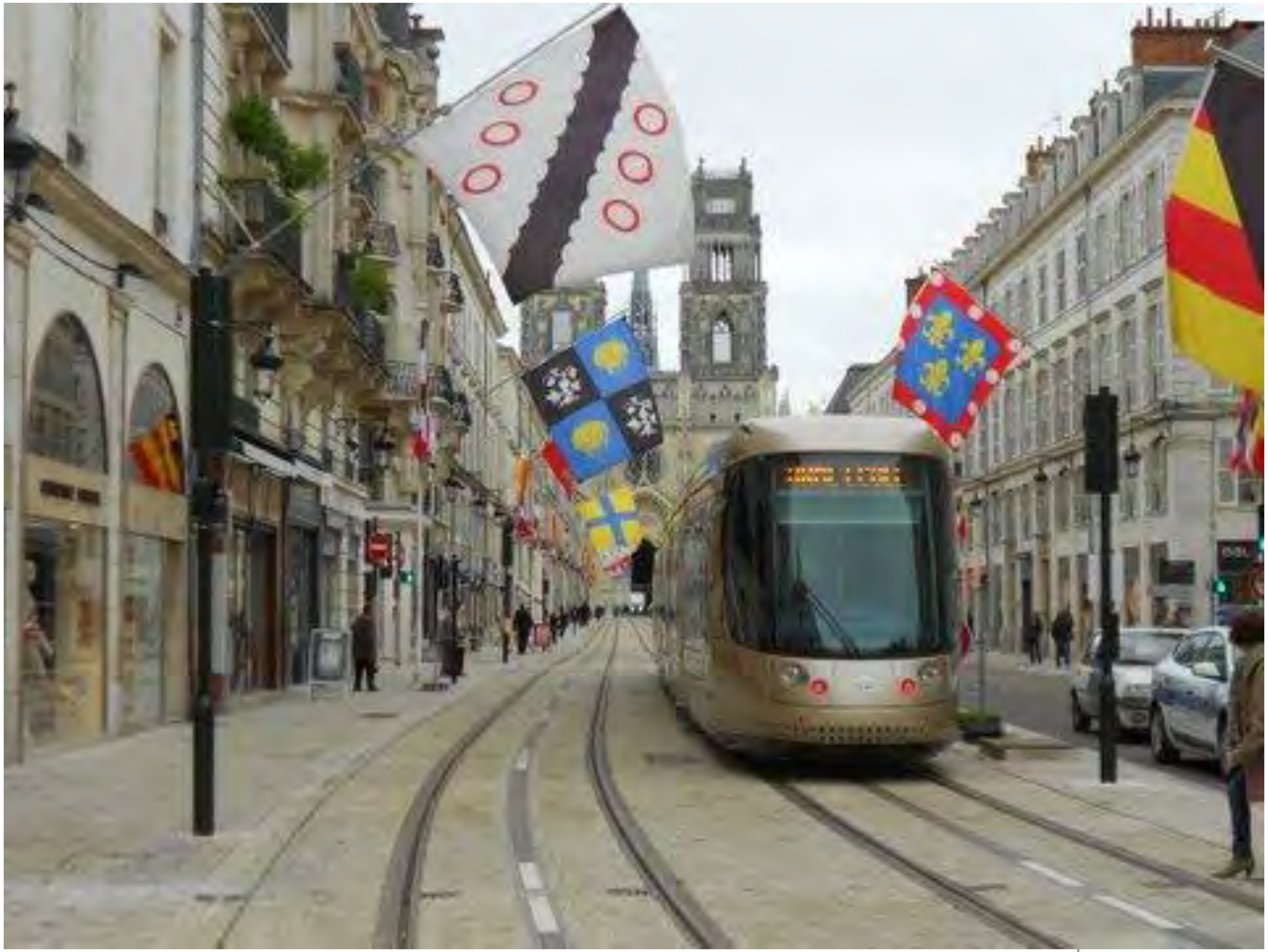
APS Main Components



TRANSPORT | ALSTOM

APS

- Final result after paving



Our Service proven solutions

APS
Aesthetic Power Supply

- In operation from 2003 (Bordeaux), 4 cities equipped, 2 more in construction.

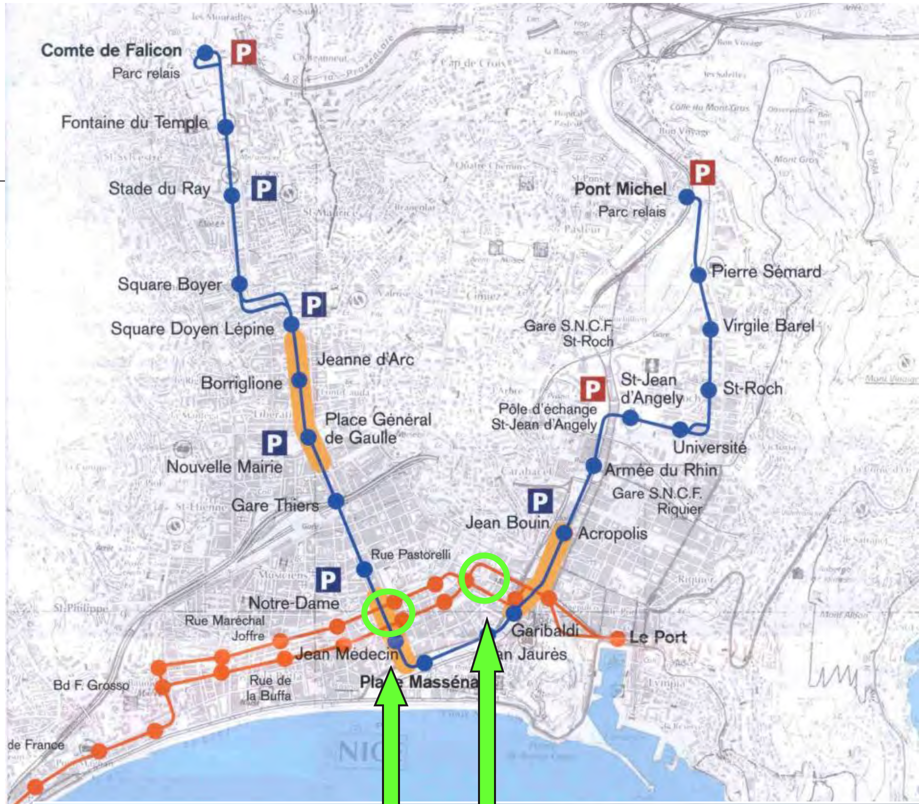
On Board Battery

- In operation since 2007 in Nice.

On Board Supercaps

- Experimentation in 2010 in commercial service with French RATP Authority.

Tram without catenary Batteries



- Service in Nice city 2007
- Two 450m sections for a total length of 9 km (8 km loading, 1 km unloading)
- NiMH battery technology (34 Ah)
- 30m Citadis Tramway

Our Service proven solutions

APS
Aesthetic Power Supply

- In operation from 2003 (Bordeaux), 4 cities equipped, 2 more in construction.

On Board Battery

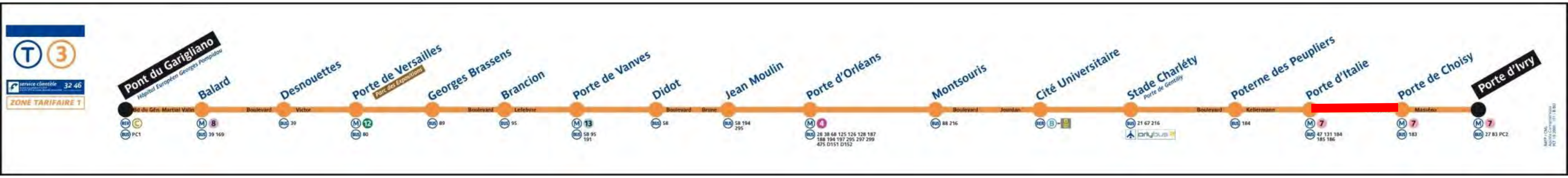
- In operation since 2007 in Nice.

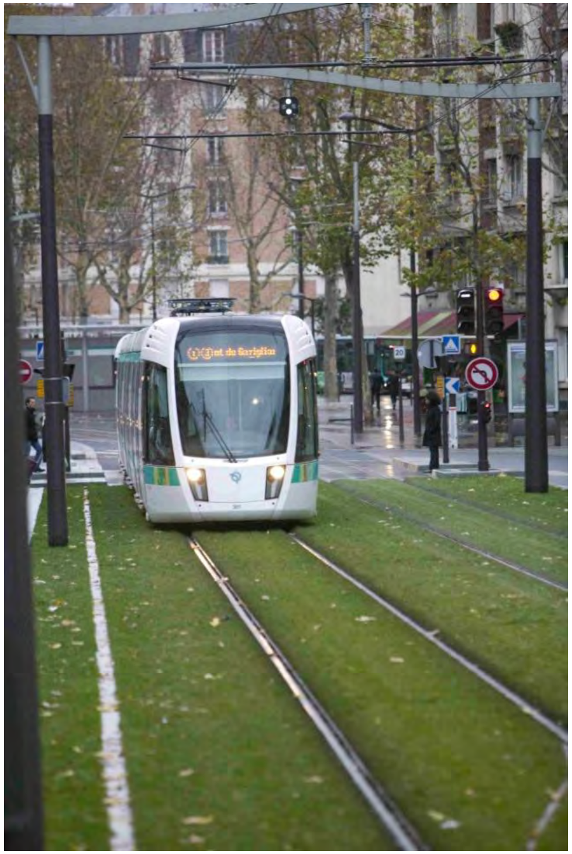
On Board Supercaps

- Experimentation in 2010 in commercial service with French RATP Authority.

On Board Supercaps

STEEM RATP





- Tramway 44 m long, 87 tons
- Running in autonomy (350m)
- Recovery of braking energy
- Quick recharge testing (20s)
- Operation in passenger service
- Supercapacitor solution

RATP

INRETS

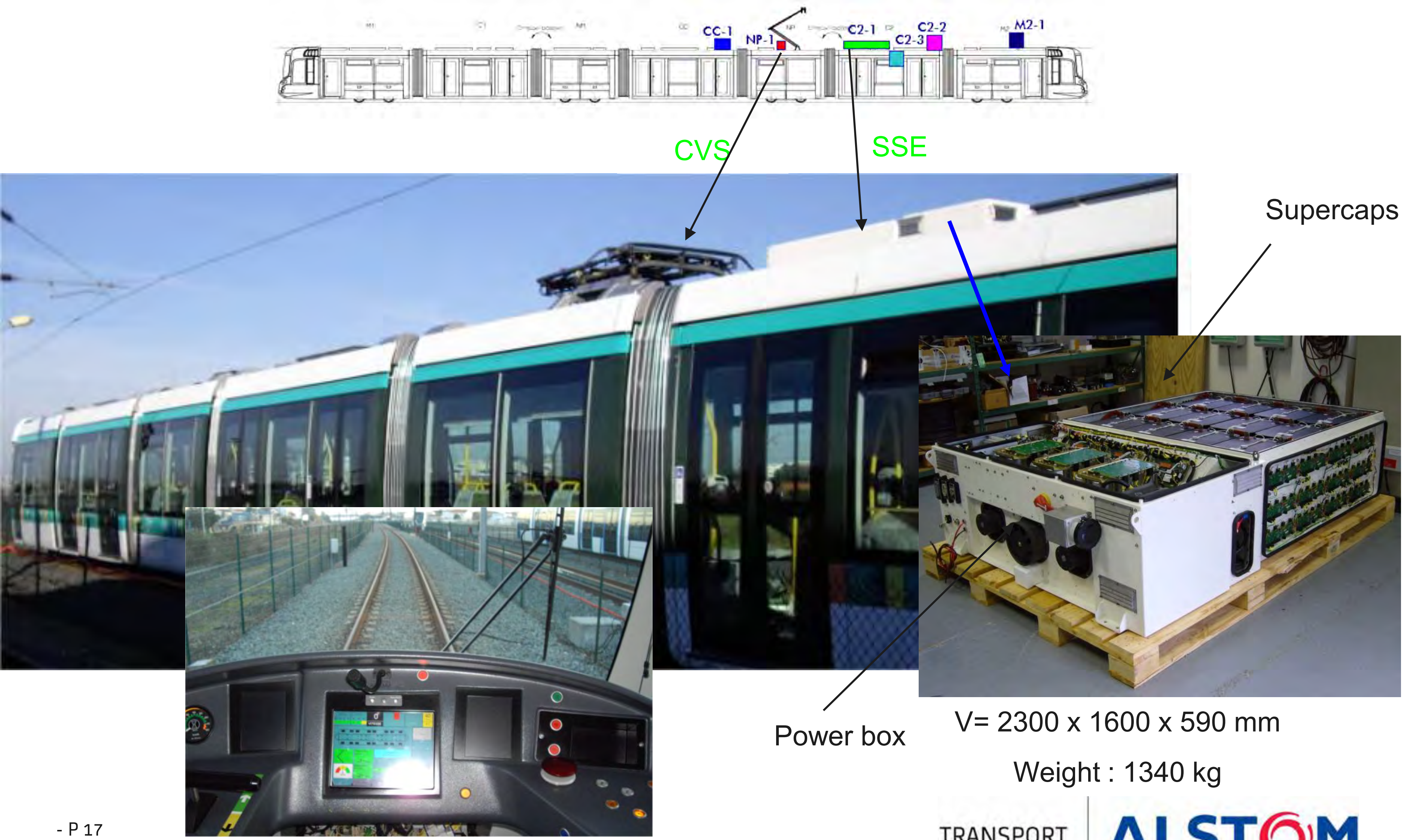
TRANSPORT

PREDIT

ADEME

Agence de l'Environnement et de la Maîtrise de l'Energie

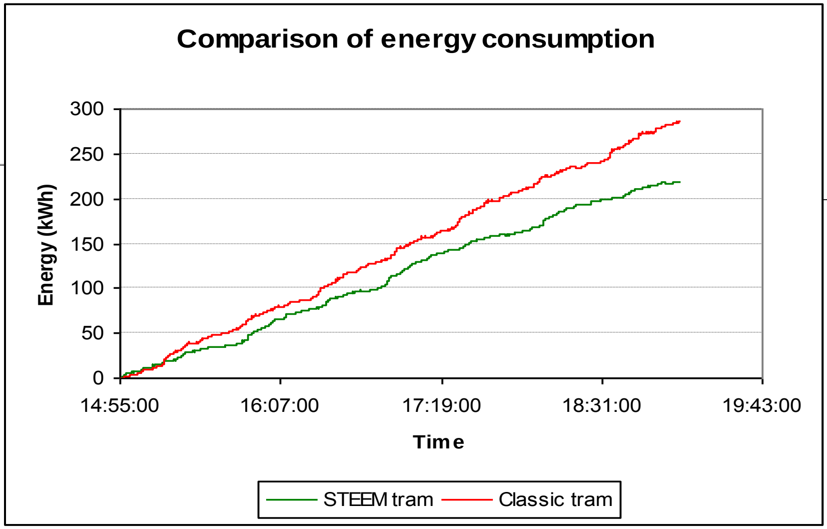
On Board Supercaps - STEEM
Tramset (n°301)roof modifications



V= 2300 x 1600 x 590 mm

Weight : 1340 kg

On Board Supercaps
STEEM RATP



Characteristics:

E	1,62 kWh
P soc1	500 kW
Msc	720 kg
Recharge	20 sec

- Running in autonomy (350 m) demonstrated.

  Expected improvements through technology evolutions: in autonomy mode
  - more than two unscheduled stops (pedestrians, vehicles)
  - emergency breaks
  - long unscheduled stops induced by road congestion

  Are requiring energy from pantograph.
- Energy saving effect (measured in spring) :
  - daily: minimum 10%, maximum 18%, average 13%
  - highest savings : off-peak hours up to 30%

Winner of the « Technology for energy and environment » prize from PREDIT, May 2011, Bordeaux, Fr

COMING ALSTOM'S CATENARYLESS SOLUTIONS

1/

Business Case

- Which expectations for ours customers ?

2/

Alstom's Service Proven Catenaryless Solutions

- Which solutions have been demonstrated as service proven ?

3/

Coming Alstom's Catenaryless Solutions

- Which solutions are we proposing now and which middle term solutions are we working on ?

ALSTOM'S CATENARYLESS SOLUTIONS
The solutions we are proposing today

APS
Aesthetic Power Supply

- APS Architecture is not modified.
- Some APS components are enhanced.

On Board Supercaps and optimized APS

- Thanks to an on board autonomy (SC), APS installation is limited.
- Portions of line (such as switches, crossroads, curves) could not be equipped.

Catenary-less evolution and benefit

Full energy (APS)

Partial energy (optimised APS + Supercaps)

Catenaryless Benefit

- Safety, Comfort, Real estate value
- Rail Attractiveness compared to other solutions
- Sustainability with cleaner energy consumption

Depending the requirement expressed in terms of catenaryless by the customer, cost effectiveness will drive the choice between APS and optimised APS and Supercaps solutions.

The solutions for on board autonomy we will propose on middle terms

- Supercaps solutions are today's solution but technology evolution are not enough full of promises in particular when questionning the stored energy compared to the weight.

Flywheel

- Williams Hybrid Power - a division of the Williams group of companies that includes the Williams F1 Team - and Alstom Transport have signed an agreement that will see Williams Hybrid Power's energy storage technology applied to Alstom's Citadis trams by 2014.

FLYWHELL

Porsche

Nürburgring

2009

Audi

Le Mans 2012

- After several years of research into energy storage, Alstom has teamed up with Williams Hybrid Power to trial its composite MLC flywheel energy storage technology which offers potential fuel savings of 15% when installed in public transport applications (buses).
- Originally developed for the 2009 Williams Formula One car, Williams Hybrid Power's energy storage technology has since been introduced into applications such as London buses and the Le Mans winning Audi R18 e-tron quattro. The technology offers fuel savings and emissions reductions by harvesting the energy that is normally lost as heat when braking and turning it into additional power. It is ideally suited to trams because of their stop-start nature and high mass. Furthermore, the flywheel's rotor is made of composite material which is inherently safe because there is no metallic structure travelling at very high speed.

FLYWHELL - From Race Car to tramway…

This new technology solutions (flywheel) are intended to fit the available space on our tram sets roof.

Ian Foley, Managing Director of Williams Hybrid Power, commented: "*From the very beginning we highlighted trams as an ideal application for our technology and to be collaborating with the market leader on this project is very exciting. We both share a common goal – developing the next generation of green transport technologies – and this agreement will hopefully prove pivotal in finding a solution that not only cuts carbon emissions but crucially cuts costs for the end user.*''

As a world leader in rail transport technology, Alstom is continuously looking to challenge and improve the energy efficiency of its trains," said Dominique Jamet, Innovation Director at Alstom Transport. "*We are proud to announce the collaborative project with Williams Hybrid Power that aims to deliver an innovative solution that does not only save energy but also re-use it to add more power to the tram while reducing energy use and CO2 emissions.*"

THANK YOU

www.alstom.com

WIRELESS POWER SUPPLY FOR TRAMWAYS

APS

MAJOR REFERENCES

🇫🇷 France: in revenue service in Bordeaux, Reims, Angers, Orleans, ordered by Tours

🇦🇪 United Arab Emirates: ordered by Dubai (tropical version)

CITADIS^{TM} tramway in Bordeaux powered by APS technology (France)

GENERAL DESCRIPTION

APS is a service-proven power system for tramways supplying electricity at ground level and therefore eliminating intrusive overhead wires. The APS catenary-less solution preserves the aesthetics of city centers, reduces track width by eliminating poles, and optimizes safety. Advantages include: no power-supply limitation; a compatibility with all types of road surfaces; and the possibility for easy extension of rail system lines. Alstom offers APS as an infrastructure kit in addition to a CITADIS rolling stock contract or as part of a turnkey tramway system contract—to ensure that our customer receives an integrated service-proven solution. Alstom also offers APS within a track and tram-fleet renovation program.

THE KEY BENEFITS

- The only service-proven catenary-less tramway power-supply system on the market: in Bordeaux, since 2003, CITADIS^{TM} tramways powered by APS have run over 11 million kilometers with a stabilized availability of over 99.7% on 13.5 km of double track.
- No power-supply limitation (as opposed to "tram-borne" power storage systems)
- High availability for optimum tram operation performance due to the simplicity of the concept based on a sliding contact of the same nature as standard metro/commuters third-rail current-collection systems
- Proven resilience in both degraded mode and disrupted conditions of service (traffic jam at intersection for instance)
- Comprehensive safety certification for passengers, pedestrians and road traffic
- Elimination of overhead obstacles (catenary) to firefighters' ladders
- Elimination of wayside masts allowing wider tram vehicles and more traffic in narrow streets
- Preservation of historic sites, trees along the track, and overall urban environment

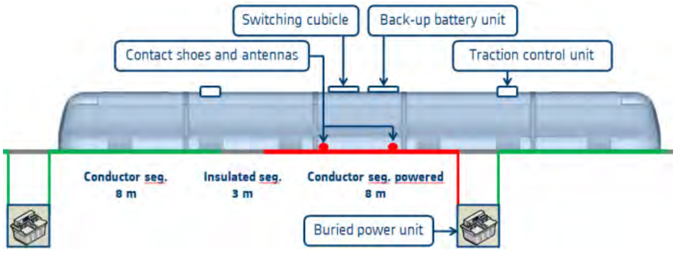
KEY FACTS & FIGURES

- **188 CITADIS^{TM} tramways** powered by APS (130 in service) have run over **12 million kilometers** to date (Feb 2013)
- **63 km** of single track equipped with APS (40 km in service)
- Availability of **99.95 %** for a **2-km** double-track application
- **No power supply limitation:**
  - Full acceleration
  - Up to 60 KPH
  - HVAC running in hot climates
  - Steep gradients
- **Complete intrinsic safety**

Alstom Transport
48, rue Albert Dhalenne
93482 Saint-Ouen Cedex FRANCE

WIRELESS POWER SUPPLY FOR TRAMWAYS
APS

MAIN COMPONENTS



- Switching and control unit: allows switching the power source between APS, catenary or back up battery.
- Contact shoes: collect traction current from the 750 V conductor rail segment.
- Antennas: emit a coded radio signal which allows detection of the vehicle by the adjacent power unit through a detection loop embedded in the third rail.
- Back-up battery unit: enables trams to run in the event of power cuts.

Power is supplied to the tram vehicle through a segmented street-level power rail embedded between the running rails in the axis of the track. Conductive segments switched off/on/off as the tram progresses, ensuring total safety for pedestrians. This third rail is made of 8 meter-long conductive segments separated by 3-meter insulating joints. Power is supplied to the conductive segments by buried power units. The electricity transmitted through the third rail is picked up by two contact shoes located on both sides of the tram central bogie.

AVAILABLE PRODUCTS

- Standard APS available dedicated for temperate climates.
- Tropicalized APS for extreme climatic conditions.

Standard APS power box

Tropicalized APS power box

KEY TECHNICAL FEATURES

> Functional features

The APS system replaces the catenary line by a proven-failsafe ground feeding system and provides the same performance as the catenary system with no power limitation.

> Configuration features

Power boxes and feeders can be either embedded between tracks or between rails, or installed under deck in case of bridge or viaduct.

> Electrical features

Power supply	750 V dc
Power consumption	Same efficiency as per catenary system

> Environment protection features

- Preserve urban environment and historical heritage
- Cope with any kind of road finishing, including grass
- Respect of EMC and acoustic constraints
- Excellent efficiency

> Environmental constraints

Outside temperature	+ 55°C max under shelter
Max. surface temperature	+ 85°C
Max. power boxes manhole ambient temperature in operation	+ 70°C

> Reliability features

Availability	99.95% for a 2 km double track application
MTTR (Mean Time To Repair)	10 minutes average
Life time	30 years

> Safety features

APS safety principle: conductive segments powered underneath tram vehicle only. As a consequence, all segments not “covered” by a tram are at the 0 V running rail voltage.

APS system’s safety has been proven through a dedicated Safety Case that was since confirmed by 5 certifying Authorities including CERTIFER and STRMTG.

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Supplier Questionnaire

The District of Columbia is currently conducting an Alternatives Analysis for the introduction of premium transit service from the Georgetown Waterfront to Union Station. As a part of this study, our technical team is charged with evaluating the feasibility of a variety of modes, including Streetcar, BRT, LRT and Premium Bus. To that end and as a part of the Streetcar evaluations, our team will also consider the feasibility of alternative propulsion and vehicle technologies in an attempt to comply with the original L'Enfant plan adopted in Washington, DC.

The operation of streetcars without overhead supply wiring is an emerging technology undergoing rapid innovation. With this in mind and realizing that the application of such technologies is greatly contingent upon factors that may not be known at this time, we are soliciting your input on the type of vehicles and their wayside requirements to facilitate the development of design concepts which maximize the potential for a competitive procurement process and minimize implementation, construction and long-term risks such as warranty and maintenance costs. Your responses and recommendations in response to any or all of the following questions would be greatly appreciated.

Question #1

The District will consider designs which allow for the use of an in-street conductor which supplies power to the vehicle continuously while operating, a system with long gaps in the overhead supply and wired areas for recharging while operating (batteries), or a system which charges an on-board storage system only when stopped at station platforms (supercapacitors or flywheels). Which of these types of systems have you supplied vehicles (rail, bus, or other transport) for? Or, are in the process of supplying? Do you have any comments on the advantages or disadvantages concerning the three system types?

ALSTOM has developed the following catenary-less solutions for light rail transit applications:

1. Full autonomy solutions using the APS in-street conductor
2. Partial autonomy solutions using batteries and/or super-capacitors
3. Hybrid solutions using a mix of technologies

1. Full autonomy solutions using the APS in-street conductor

The APS in-street conductor technology supplies power to the vehicle through a power line which is embedded in the street in the middle of the alignment, between the two running rails. The power is fed continuously to the vehicle through a live section of the APS power rail. As the vehicle runs along the line, power switches embedded in the street activate and de-activate the live section located under the middle of the vehicle.

APS is in revenue service in the following cities:

- Bordeaux since 2003
- Reims since 2011
- Angers since 2011
- Orléans since 2012

APS will be used on the following lines that are currently under construction:

- Tours where commercial service is planned in September 2013
- Dubai where commercial service is planned in November 2014

The APS in-street conductor proven technology has been delivered by ALSTOM for more than 15 years as part of an integrated electrification and vehicle solution for light rail networks requiring off-wire operation. ALSTOM's shoe collector equipment could be made available to rolling stock manufacturers and fitted to most light rail vehicles if a network and its fleet were to be expanded with the APS in-street conductor technology. Conversely, vehicles equipped with other autonomy solutions could be used on a network equipped with the APS in-street conductor technology.

This APS in-street conductor technology has acquired more than 7.5 million miles (12 million kilometres) of experience in revenue service. More than 25 miles (40 km) of single track are in operation with the APS in-street conductor technology today and 130 ALSTOM light rail vehicles are equipped with APS.

A full presentation of the APS in-street conductor technology and the projects mentioned above is given in appendix "APS Presentation 2013-03-08 V1.ppt".

The main advantage of the APS in-street conductor technology compared to partial autonomy solutions such as batteries or super-capacitors is that the vehicles can be operated with the same level of performance as with overhead catenary. More specifically, the benefits versus other catenary-less solutions are:

- no power limitations in slopes
- no distance limitations between stations
- no power limitations to auxiliaries and/or HVAC in downgraded modes of operation
- no power limitations at intersections or during unexpected service stops
- no special requirements impacting sub-station design and capacity

2. Partial autonomy solutions using batteries and/or super-capacitors

ALSTOM has also delivered partial autonomy solutions based on batteries and super-capacitors. Vehicles equipped with batteries are in service in Nice since 2007 and prototype vehicles equipped with super-capacitors have been delivered to RATP in Paris (STEEM technology, see video attached) and put into commercial service in 2009.

The main differences between batteries and super-capacitors are the following:

- Batteries allow the storage of a significant amount of energy but the rate at which the energy can be extracted (or recharged) is limited. Hence, their power is limited.
- Super-capacitors on the other hand are not power limited but the amount of energy that can be stored in a given volume is rather limited compared to batteries.

In order to accelerate a vehicle and to maintain its speed, a certain amount of power is needed. Super-capacitors are best able to meet the peak accelerations and speeds.

On the other hand, travel over a given distance requires a certain amount of energy. If the distance is too long, a super-capacitor will not have enough energy. Then, using a battery will be more appropriate.

In order to address this problem, one solution is to use a mix of both technologies, i.e. super-capacitors to accelerate the vehicle associated with batteries for longer distances and for vehicle rescue in emergency conditions. ALSTOM is currently developing this hybrid design.

Another partial autonomy technology which offers a good compromise between power and energy is the flywheel but this technology is only in its early development stage for rail applications.

It is important to note that for all on-board partial autonomy technologies, the energy storage system must also supply the auxiliary loads of the vehicle. The highest loads are the air-conditioning and/or the heating of the vehicle which are significant when compared to the requirement for tractive power (typically 30-40kW of power in a 90 foot streetcar or light rail vehicle). So, in practice, the distances which can be covered by these systems are greatly reduced when considering real operation with auxiliaries.

3. Optimal hybrid solutions using a mix of technologies

Based on its experience with both the APS in-street conductor technology and super-capacitors, ALSTOM is now proposing solutions which incorporate a mix of both of these technologies. The objective with this approach is to achieve the best compromise between the system's overall performance and its associated capital and lifecycle costs. This is achieved by implementing the APS in-street conductor only in areas where the energy needs are the most important, i.e. in stations for recharging, over long stretches of the alignment without stations, in steep grades, ahead of large intersections, etc.

Today, depending of the needs of each project, ALSTOM can propose the APS in-street conductor technology, batteries, or super-capacitors or a hybrid solution using both APS and super-capacitors

Before recommending any solution ALSTOM would evaluate the unique service requirements of each customer and would propose a system which would attempt to optimize the following tradeoffs:

- Operational requirements in terms of performance, headways
- Power and energy storage requirements versus vehicle weight and space constraints ;
- Recharging times versus dwell time and headway requirements
- Impact of recharging times on substation design
- Impact on service of degraded modes
- Estimated life of technology versus life of system and cost of replacement of power source
- Depending on the procurement scheme, the optimized compromise between capital cost and lifecycle cost.
- Technology Maturity of technology versus reliability requirements

A complete presentation of ALSTOM’s present offer is given in appendix “ALSTOM's catenary less solutions Presentation 2013-03-08 V5.ppt”.

Question #2

A traditional streetcar is designed to operate from an overhead supply system operating continuously at either 600 or 750 Vdc. Would your company’s offering place any special or additional requirements concerning integration of the electrification system? Would your technology operate with a pantograph when not on a wireless section?

The APS in-street conductor technology’s nominal voltage is 750 Vdc with a 900Vdc maximum and a 500Vdc minimum. The APS power boxes and cable ducts would need specific underground sections.

The APS power boxes and cable ducts have specific underground volume requirements. The APS power boxes have a footprint of 5 ft 3 inches x 2 ft (1.6m x 0.6m).

The APS cable ducts need to be positioned at a depth of 1 ft 4 inches (0.4 m) and have a cross-section of 2 ft x 8 inches (0.6 m x 0.2 m).

The Citadis streetcar will operate with a pantograph when not running on a wireless section.

Question #3 - In Street Conductors

Has the in-street conductor been utilized in areas which normally experience snow and ice in the winter? What material would you use for fabricating in-street conductors? Would the material show corrosion for the application of de-icing road salt? What provisions are made to prevent snow plow blades from damaging the rail?

APS has been utilized in area with snow (see the videos attached in appendix from the Reims project “video-2013-01-15-08-39-23-rotate.avi” and the Angers project “Neige hyper-centre Angers.mp4”).

It is important to note that road salt is not to be used for de-icing. In cities where the APS in-street conductor technology is used, the operators and municipalities use a biodegradable de-icing fluid. Coordination is required between the municipality and the LRT operator to ensure that there is no salt exposure of the portions of the rail alignment equipped with the APS in-street conductor technology.

Use of snow plows over portions of the rail alignment equipped with the APS in-street conductor technology are not an issue. Plow blades equipped with a special rubber end can be used as an added precaution (as is the case in Bordeaux for example).

Question #4 – In Street Conductors

Has the in-street conductor been installed in mixed use traffic lanes?
Has it been installed in reserved lanes with normal traffic operating at right angles across it?
Have there been any issues related to cleanliness resulting from contamination with rubber tire, oils, or autumn leaves?

The APS in-street conductor technology and its associated power rail have been installed in mixed use traffic lanes (see pictures below).

Picture from Reims

Picture from Orleans

The APS in-street conductor technology can be installed in dedicated lanes or in mixed use traffic lanes with normal street traffic operating at angles across it.

In case of very heavy traffic a special maintainable section of the APS power rail can be installed. If damaged, this section of the power rail can be replaced within 4 hours when the service is not in operation or during scheduled maintenance periods.

There have been no issues related to cleanliness resulting from contamination with rubber tire, oils or autumn leaves during the past 10 years and 7.5 million miles of operation of the APS in-street conductor technology.

Question #5 – In Street Conductors

How is the conductor installed in the street? Give short explanation and provide APS technical sheet + APS ppt presentation.
Are there any restrictions on horizontal or vertical curvature of the pavement?
How are crossings or turnouts implemented with the conductor rail? We prefer hybrid solution please develop
What clearances are required for other structures such as manholes and metallic covers?

The APS power rail is positioned at a height 0.5 inches (12mm) above the Top of Rail.

There is a 2% slope from the APS power rail down to the running rail to avoid water puddles.

Crossings or turnouts are equipped with the APS power rail. In these situations, the APS power rail is installed at the same height as the Top of Rail to ensure a smooth transition of the collector shoes when crossing the running rails.

The APS technology data sheet is provided in appendix “APS_TGS Technical datasheet_08-04-13_SB_PM_V5.doc”

Question #6 – Batteries

Which battery type do you have experience in applying, Lithium (Li) or Nickel Metal Hydride (NiMH)? What is the maximum acceleration rate and maximum speed normally used in these applications?

ALSTOM has applied NiMH batteries on the Nice streetcar system which is in service since 2007. The maximum speed running on batteries is 19 mph (30 km/h) and the maximum acceleration rate from 0 to 19 mph (30 km/h) is approximately 0.45 m/s^2 in AW0 load (empty vehicle) and without any grade inclination.

The Nice project was developed nearly 10 years ago and ALSTOM would apply Lithium batteries on a similar project today since they are lighter and have a higher performance (although more costly).

The total current and power that can be drawn from the batteries will depend on the number of battery cells on-board the vehicle. Therefore, the maximum operating speed and acceleration will also vary with the number of batteries on-board the vehicle (see next question #7).

Question #7 – Batteries

What are the design limits and emergency limits for charge/discharge levels of the batteries on your vehicles? Is the battery management system provided by the battery manufacturer, third-party specialized supplier, or incorporated into the propulsion system? Are the individual cells monitored?

The design limits and emergency limits for charge/discharge levels will depend on the battery technology used.

In the case of the Nice project where ALSTOM has used approximately 2 tons of NiMH batteries with an average useful stored energy of 5kWh and a maximum useful stored energy in downgraded conditions of 15kWh, the maximum charge and discharge currents are respectively 22 Amps and 220 Amps. The maximum discharge power for this application is 200kW (approximately 100kW per ton of batteries).

The batteries are only discharged by about 10% to 15% in normal use in order to ensure a battery life of 5 to 8 years. In emergency situations, the batteries can be discharged much more (to less than 50%).

The Battery Management System (BMS) is provided by the battery supplier. However, the battery management system is incorporated into ALSTOM's propulsion system and ALSTOM is responsible for the energy management and other functional aspects of the vehicle controls.

The cells are not controlled individually. They are grouped in modules of 10 cells each module being individually controlled.

Question #8 – Batteries

The operating environment in DC has a temperature range of -15°F to 106°F. What will be used for the cold temperatures to ensure proper operation of the system? Do the high temperatures with added solar heat gain prove detrimental to the batteries? Is a heating and cooling system typically provided for the batteries?

In order to provide their specified performance, batteries must be maintained within a certain temperature range. ALSTOM's battery system is equipped with a cooling system (Battery Thermal Monitoring System) which maintains the cells at a defined temperature (depending on the season). The battery, battery charger, BMS and temperature control system are all integrated in a single equipment case.

For super-capacitors, similar considerations will apply even if they are more tolerant to temperature extremes.

Question #9 – Batteries

There is a concern with impacts damaging Li batteries with fires resulting days later. This was observed during crash testing of the Chevy Volt. Are the batteries located in an area susceptible to impacts in traffic accidents? Have you established criteria for maximum impact shocks and have the criteria been validated by the battery manufacturer?

In ALSTOM's off-wire rail applications, the batteries are located on the roof of the vehicle. The ALSTOM batteries are tested and validated to withstand shocks and vibrations as par the EN 61373 standard.

There are many different technologies grouped under the general category of "Lithium ion" batteries (about 25 different chemical and physical compositions exist on the market). Each has advantages and disadvantages with respect to power, energy storage capacity, service life, and safety. ALSTOM applies battery technologies which are the most suitable for a railway environment and which minimize fire risk. ALSTOM's design approach for streetcars and light rail vehicles is to install equipment on the roof in order to maximize space and accessibility for passengers and also due to the special low floor design of ALSTOM's vehicles. This has proved to be the best choice also in terms of impact protection and safety. Shock, crush, and puncture testing are part of the many validation tests carried out when selecting batteries for our applications. In any event, after a collision a complete examination (including some specific testing) of the vehicle and its systems would be performed before its release back into service.

For super-capacitors, the same principles and considerations would apply regarding installation on the roof and validation testing.

Question #10 – Batteries

Batteries will be discharged during overhead gaps and recharged while operating in wired sections. As a "ball-park" approximation, if a streetcar traveled three miles off wire with 6 stops on an average 2% grade how long would the vehicle need to travel on wire to fully recharge? What would be the maximum current draw for battery recharging?

A 60 ton vehicle traveling a distance of three miles off-wire with 6 stops on an average 2% grade would require approximately 30kWh of useful stored energy on-board in a normal mode of operations (including power for auxiliaries and HVAC). Our experience on the Nice Project has shown that the maximum recharge current for batteries meeting such an energy requirement would be of about 80 Amps and that the recharge time running on wire would be approximately 2 hours.

Question #11 – Batteries

If a stationary vehicle draws the maximum current for battery recharging in addition to the vehicle's maximum auxiliary power requirement on a 106°F day in full sun with no wind, is it possible to heat a 350 kcmil overhead contact wire to the 160°F annealing temperature of the copper? If so, what measures may be taken to mitigate this concern?

ALSTOM has not encountered such situations and we have not made the calculation but this risk seems unlikely since the maximum recharging power of batteries is typically several times lower than the discharge power. If the particular environmental conditions and recharge rate of the batteries were to confirm such a risk, the simplest solution for a vehicle under pantograph would be to double the number of contact wires used in the area of "charging at standstill".

Question #12 – Supercapacitors

What is the time required to recharge fully depleted supercapitors at a stop? What level of current and voltage is this time based on?

Base on ALSTOM's experience, the recharge time for a fully depleted 1,2kWh/300kW super-capacitor module is 18 seconds. The current will be approximately 400 Amps under a 750V catenary.

Question #13 – Supercapacitors

For a discrete charging system, would your firm recommend a traditional supply system with distribution via underground conduit or smaller discrete chargers at predetermined locations? If discrete chargers are possible, what is the range of AC supply voltages that could be accommodated? Can a one-line diagram of such a discrete charger be provided?

ALSTOM does not have experience with the distribution of small discrete chargers located along the alignment. It would seem that this type of solution could be less competitive in terms of wayside infrastructure than the in-street conductor technology. This solution would also likely have an impact and impact on trip time compared to the in-street conductor technology (recharging time at discrete locations).

Question #14 – Supercapacitors

If station spacing of one-half mile (800 m) on a 2% grade and the streetcars stops for traffic signals every 500 ft (150 m) is used, would your standard vehicle be capable of passing a stop without charging while operating with the maximum auxiliary load, including HVAC? What would be the anticipated charge level remaining at the second stop?

The route profile described above with recharging of the super-capacitors at each station stop would require the streetcar to have a useful stored on-board energy of approximately 7-9 kWh depending on the actual vehicle weight and size, HVAC characteristics, and tractive power characteristics. The corresponding system of super-capacitors would weigh roughly 6-7 tons. Fitting our standard vehicle with such super-capacitors would be impossible and would require a re-design.

If the intent of question #14 is to explore the possibility of recharging at traffic stops along the route alignment as opposed to recharging at station stops, then it is important to note that:

- each stop in the route profile described above would draw about 0.7kWh of stored energy ;
- recharging at traffic stops would require about 15 seconds at standstill ;
- recharging only at station stops would require about 2-3 minutes.

It is also important to note that even assuming recharging at determined stop points along the alignment, the streetcar would likely need to be given traffic priority over other vehicles and isolation from pedestrians may also be needed to avoid any unplanned prolonged stops that would drain the energy source and leave the vehicle stranded without power.

Question #15 – Batteries & Supercapacitors

Under lane-sharing scenarios, a Streetcar could be delayed considerably in traffic resulting in insufficient remaining charge to reach the next charging area. What is your strategy for minimizing this risk? Would additional storage capacity or capacity monitoring and load shedding (HVAC) be used? What is the possibility of recharging the vehicle in the street and what equipment would be recommended?

Our system will monitor charge level and, in case the charge level becomes too low, load-shedding will be applied (HVAC). This type of strategy was implemented on the Nice streetcar.

For in street charging, a small genset vehicle could be used. Another solution would be to have a towing vehicle.

Question #16 – Vehicle Design Criteria

The District currently owns three T12 streetcars manufactured by Inekon and has three American-built versions of the Skoda T10 streetcars on order. These vehicles use the standard Czech width of 8 ft (2.46 m). What are the implications of continuing to use such European dimensions? Would you be interested in proposing on a small order of 8-10 cars with this width requirement? If no, what is the minimum order size you would be interested in? Would you prefer using the typical US width of 8 ft 8.3 in (2.65 m)?

ALSTOM would not be interested in proposing an 8 foot wide vehicle even for higher quantities. We would propose our 8 ft 8.3 in (2.65m) wide "CITADIS Spirit" that has been specifically adapted to meet the unique needs of the US market. A high capacity version of that vehicle (48m length) will be built in ALSTOM's facility in upstate New York (production in 2015 through 2017 for base contract). This vehicle offers proven, industry leading technology as well as world-class design to integrate into the urban environment. This vehicle draws upon the experience of more than 1,600 CITADIS vehicles is service in more than 40 cities in 12 countries.

Question #17 – Vehicle Design Criteria

The District's current vehicle design criteria limit the length of the vehicles to 72.2 ft (22 m). Does this length permit sufficient space to mount energy storage devices on your standard vehicles? If not, what is the minimum length of vehicle your firm would be interested in providing?

Such small vehicle dimensions do not allow the use of any of the catenary-less solutions using batteries, super-capacitors or the APS in-street conductor technology.

1) Vehicle equipped with super-capacitors

A 22 m vehicle would realistically be able to accommodate only one or two super-capacitor modules weighing approximately 2-3 tons in total (depending on the technology and design) and with a total stored energy of about 2-3 kWh. In normal load conditions (i.e. AW3 load with a vehicle weight of approximately 50 tons), the vehicle would barely be able to run over a distance of 400 meters at a 2% grade and would not be able to re-accelerate in the event of an unplanned stop.

2) Vehicle equipped with batteries

A vehicle equipped with batteries would require a total average useful stored energy capacity of at minimum 16 kWh in the following operating conditions:

- 2 mile off-wire section at a 2% grade and a maximum speed of 20 mph (30kph)
- no unplanned stops on the route, no towing of vehicles
- 4 stations with one-minute dwell time at each stop
- normal auxiliary and HVAC loads

In these same normal operating conditions the on-board batteries should be designed to have a maximum useful stored energy capacity of approximately 30-40kWh for downgraded conditions and to allow for a sufficient battery life.

In such conditions and based on our experience on the Nice project the vehicle would require at least 6 tons of on-board batteries. A 22 meter vehicle with only 4 axles would not be able to accommodate 6 tons of on-board batteries due to layout and axle load limitations.

3) Vehicle equipped with APS technology

The safety case for the APS in-street conductor technology requires a vehicle length of at least 28m to ensure that the live section of the power rail is always in a protected area under the middle of the streetcar.

Moreover, for its integration under the vehicle, the APS shoe collector requires a non-motorized truck and therefore a vehicle length of at least 27m.

Question #18 – Retrofit of Existing Vehicles

The District currently has vehicles with lengths of 66 ft (20 m) and width of 8 ft (2.46 m). If these vehicles are to be operated on lines with wireless sections they will need to be retrofitted. What would be the approximate space requirements if your technology were to be retrofitted? Are there any proprietary components that would be required? Do you have any experience retrofitting the system to older vehicles manufactured by you or others? Would you be interested in performing the retrofit work as part of a new procurement?

ALSTOM has the largest experience in fleet renovation in the USA (including light rail vehicles). However, ALSTOM would not be able to perform such a retrofit work as part of a new procurement due to the impossibility of having a catenary-less solution applied to such vehicles (see answers to questions #16 and #17).

Question #19 – Specialized Equipment

What specialized equipment will be required to maintain your proposed energy storage and/or enhanced propulsion technology options? Will additional shop equipment or storage/charging rooms be required? Will test and troubleshooting procedures be impacted, particularly for high voltage storage devices on the vehicles? Please elaborate on the specific function and purpose of such equipment.

The testing of the traction system including the APS is fully integrated into the vehicle and is part of the automated function of the traction control system. Trouble shooting is also part of the automatic traction control systems.

No special specialized shop equipment will be required for the maintenance of the APS shoe collector.

Safety procedures are applied for the discharge and handling of high voltage storage devices. These form part of the maintenance instruction of the vehicles. The storage procedures are no different from those required for normal traction capacitors.

The APS system and the on-board energy storage devices will require the following specialized maintenance equipment and/or functions:

- a battery charge-discharge testing area (charging and discharging of batteries),
- an APS power box repair bench for troubleshooting and repair of the power boxes that activate and de-activate the live sections of the APS power rail depending on coded train signals,
- an APS SCADA control center that monitors and controls the power boxes on the line,
- a portion of the APS line in order to perform train testing

Question #20 – Training and Education

Will additional specialized training for vehicle maintainers, wayside maintainers, or vehicle operators be required? Will specialized personnel in any of these areas be required or would a typical maintainer/operator with a high school diploma and standard maintainer/operator training be sufficient?

No specific diploma required but specific training that has to be provided to the following categories of personel :

- wayside maintainer : maintenance procedures of Power boxes and substation power modules
- on-board maintainer : maintenance of batteries, battery chargers, collector shoes and antennas
- vehicle operator : operation of APS at the entrance and exit of APS in-street conductor areas

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